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PHYMATOTRICHUM (COTTON OR TEXAS) ROOT ROT IN ARIZONA

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SYNOPSIS

Phymatotrichum root rot is widely distributed in the semiarid Southwest and on the eastern and western coastal plains of the Republic of Mexico. It has not been found in other countries.

Root rot is caused by a soil-inhabiting fungus, *Phymatotrichum omnivorum*, which is indigenous to the Southwest where soils are alkaline and low in humus and the winters are mild. While it is able to attack native vegetation, it is not often destructive.

The fungus attacks the roots of susceptible plants causing them to decay which results in the death of the plant. While the fungus is more or less active the year round, the disease is conspicuous only during hot weather—July to mid-October in Arizona. During this period affected plants wilt and die suddenly.

The root-rot fungus attacks over 1,700 species of plants including not only a majority of cultivated plants such as field crops, garden and truck crops, deciduous fruit trees, nut trees, shade trees, shrubs, and other ornamentals but also weeds and native vegetation. The only plants which as a group are immune from attack are the monocotyledons.

The vegetative (*Ozonium*) stage of the fungus consists of strands of interwoven filaments occurring on diseased roots. The spore mat (*Phymatotrichum*) stage, found on moist soil surfaces near dead or infected plants, is usually produced only during the late summer months. Resting bodies, or sclerotia, are formed in the soil near the diseased roots and enable the fungus to survive unfavorable conditions.

The root-rot fungus spreads from plant to plant along the roots, or through the soil independent of roots for short distances. The fungus penetrates susceptible roots in many places.

The fungus may overwinter in several ways: (1) in an active vegetative condition in infected but still living plant roots; (2) on the deeply buried dead roots of susceptible trees; or (3) in a dormant condition in sclerotia or sclerotial strands.

Root rot is one of the most difficult of all plant diseases to control on account of its very extensive host range and the difficulty of eradicating it from infected soil. Rotation with nonsusceptible crops, together with clean culture, is the most economical control where large areas in field crops are involved.

Control by means of heavy applications of ammonium compounds has proved practicable for small areas where valuable orchard crops or ornamental plantings are involved.

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PHYMATOTRICHUM (COTTON OR TEXAS) ROOT ROT IN ARIZONA

By R. B. Streets

INTRODUCTION

Of all the plant diseases which harass the farmer in Arizona and certain other parts of the semiarid Southwest perhaps the most destructive, and certainly one of the most difficult to control, is cotton root rot, often known also as "Texas root rot" or simply "root rot," and sometimes in the literature as "Ozonium root rot" or "Phymatotrichum root rot," names adapted from the scientific names of the causal organism. The use of the unqualified name "root rot" is undesirable as it does not distinguish this particular disease from a large number of other root-rot diseases caused by various organisms, and this leads to confusion. "Cotton root rot" was adopted in 1929 as the common name of the disease at the root-rot conference at College Station, Texas, and has the advantage of being the first common name used for the disease in 1888 and 1890, in fact up to 1923. The present trend seems to be toward the use of "Phymatotrichum root rot," a name which distinguishes this disease from all others but which may prove difficult to the layman.

Phymatotrichum root rot, although it was first studied in 1888 and has been under investigation more or less continuously since 1906, still presents many baffling problems to both the farmer and the investigator. There have been published some 120 scientific papers on this disease, and it is the writer's aim to bring together the results of his studies on Phymatotrichum root rot under Arizona conditions with pertinent summaries of the work of other investigators to produce a bulletin primarily for the use of the residents of Arizona in combating this disease. In order to aid individuals who may wish more detailed information than it is possible to include in this bulletin and to make this paper more useful to other investigators, reference numbers to the citations listed in the Literature Cited at the end of the bulletin are given in parentheses. Users of this bulletin will also find the Table of Contents of great assistance in finding information on specific phases of the root-rot problem.

PREVIOUS INVESTIGATIONS

Before 1888 when Pammel (91) announced that the mysterious disease which had been killing cotton plants for years in Texas was due to a fungus which invaded and killed the cotton roots,

cotton growers and others had been attributing the dying of plants to a variety of causes including alkali and weather conditions. Pammel (91) suggested that root rot might be controlled by proper rotation of crops and later (92) reported its successful use by farmers. Curtis (9) in 1892 describes a root rot of alfalfa in Texas caused by a fungus identified by Atkinson as "*Ozonium auricomum* of Pammel" from cotton. In 1907 Shear and Miles (110) recommended deep fall or winter plowing combined with crop rotation as a means of controlling root rot.

The same year (1907), Shear (109) described the vegetative stage of the organism giving it the name *Ozonium omnivorum* Shear. The disease was first recognized and identified in Arizona by J. W. Toumey (151) who reported its causing a root rot of alfalfa in 1898. J. J. Thornber (150) was the first to describe and to recognize the connection of the spore mats on the surface of the soil with the vegetative stage underground. Papers by Heald (39) and Heald and Wolff (40, 41) from 1909 to 1912 record the increasing importance of root rot in Texas. The conidial stage of the fungus produced in the spore mats was described in 1916 by Duggar (16) who gave it the name *Phymatotrichum omnivorum* (Shear) Duggar.

From this time on, investigations of the root-rot disease were undertaken in earnest by two agencies: the Texas Agricultural Experiment Station and the U. S. Department of Agriculture with field stations at San Antonio (1916) and Greenville, Texas (1919), and Sacaton, Arizona (1917).

Scofield (107, 108) reported the progress of field studies begun in 1916 at the San Antonio station in 1919 and 1921. In 1934 Ratliffe (99) published results of rotation and tillage experiments at the San Antonio station over a period of twenty-one years, showing that a four-year rotation is necessary to greatly reduce root rot, and that the persistent centers of infection could be traced to deeply buried material such as tree roots on which the fungus maintains itself saprophytically for long periods.

The effectiveness of clean fallow in the control of root rot has been studied by McNamara at Greenville (63); King and Loomis (56, 57) at Sacaton; and Taubenhaus and Killough (148), Reynolds and Killough (101), and Rea (100) of the Texas Agricultural Experiment Station.

The use of natural organic fertilizers and chemical fertilizers for root-rot control has been studied incidentally or very thoroughly by practically every investigator who has worked on the control of root rot. Among the reports most worthy of notice are the extensive experiments with commercial fertilizers by Jordan and Dawson and their associates (43); experiments with heavy applications of organic fertilizers by King and associates (47, 52, 54, 55); experiments with ammonium compounds by Neal and associates (77, 78, 79, 83, 86, 87); and experiments of Taubenhaus and Ezekiel (139).

The discovery of the sclerotial stage of the root-rot fungus in culture by King and Loomis (57) and the finding of sclerotia in

Plate II.—Deciduous fruit orchard seriously affected by root rot. While some crown gall is present, root rot accounts for nearly all of the missing trees. Kinds of trees from front to back: apple, pear, plum, and peach.

soil by Neal (76) and their production in soil cultures by Dana (11) proved to be of considerable value in explaining the erratic behavior of the fungus. A contribution of similar importance was made by Dana (10) who described the occurrence and infectious nature of smooth or "horsehair" strands found in primary centers of infection in cotton following an eighteen-month clean fallow.

Taubenhaus and his associates early began a tabulation of plants susceptible and resistant to root rot. The first fairly comprehensive list by Taubenhaus and Killough (148) enumerated 169 susceptible species. By 1929 Taubenhaus, Dana, and Wolff (131) had increased the susceptible list to 518 species; and a recent third list by Taubenhaus and Ezekiel (145) shows 1,708 susceptible species with a rating of their relative susceptibility.

Likewise worthy of mention is the work of Bach (3) on the relative resistance of citrus root stocks to root rot and on the resistance of Turk's-cap hibiscus (4, 5); of Butler (7, 8) on the susceptibility of watermelon in Arizona; of Dana, Rea, and Dunlavy (12, 13) on effect of date of planting; of McNamara, Wester, and Gunn (67, 68, 69, 70) on life history, morphology of the fungus, persistent strands, and sclerotia forming habits; of King, Hope, and Eaton (51, 53) on natural occurrence of the root-rot fungus on desert plants; of Ezekiel, Taubenhaus, and Fudge (31, 32, 34, 138, 140) on the nature of resistance of monocotyledons to root rot; and of Taubenhaus and Dana (129) on the influence of moisture and temperature upon root rot. Summaries of results reported at four root-rot conferences have likewise been published (19, 20, 21, 22). Many additional contributions by the above mentioned investigators and others have added to our still incomplete knowledge of Phymatotrichum root rot.

A very complete compilation of literature on root rot including a bibliography of 255 titles has been published in Russia (14), and strict quarantine measures now guard the U.S.S.R. against importation of the disease.

EARLY RECORDS OF ROOT ROT IN ARIZONA

As early as 1898, Toumey (151) reports that "the disease has not been confined to alfalfa, but in certain localities has caused much injury to apples, peaches, apricots, almonds, many small fruits, and a great variety of ornamental trees and shrubs." Following this Tyler (152) in 1900 and Griffiths (38) in 1901 describe briefly attempts to control root rot in alfalfa by chemical treatments. In 1906 Thornber (149) published the first description of the spore mats of the fungus, and in 1917 (150) he reported it on white sweet clover in the Sulphur Springs Valley. Plant disease surveys by Brown (6a, b, c) from 1920 to 1922 showed the disease to be prevalent and destructive in most of the cultivated areas in southern Arizona.

PRESENT PROJECT

The writer's experience with the disease began in 1925 and since that time studies on selected phases of the root-rot problem have been continued and expanded as the time and funds available permitted. Earlier studies were centered around the seasonal development of the disease, symptoms on various host plants, and the possibility of control by rotation, cultural methods, and selection of resistant strains of cotton (114, 116). Several years later the need for a satisfactory treatment to control the disease in valuable orchard and ornamental plantings became so apparent that a study of various fungicides and other chemicals for soil treatment was undertaken. Formaldehyde and similar volatile compounds were known to be effective but too toxic to be used on or near infected living plants. Solutions of copper sulphate and of sulphuric acid were found to be toxic to the fungus but were too active with normal soil constituents, and frequently the treated trees seemed too weak to repair the damaged root systems (114). Since 1932 soil treatments in the field have been made with various ammonium compounds which, on account of their nitrate content, furnish plant food in abundance to aid the recovery of the treated trees and have given satisfactory response following treatment (119, 122). The treatment of soils before planting of susceptible trees as insurance against future attacks is one of the most recent lines of investigation which from preliminary data shows promise (124).

Every year some additional species of plants have been found to be susceptible to root rot. Some deviations from published ratings (118, 121, 123) likewise have been found in the degree of susceptibility of species. For example, pecan, white potato, watermelon, and Osage orange were found to be moderately susceptible at a time when they were rated immune. Also Arizona grows some species not cultivated in the other states where root rot is found, so data are being sought on the reaction of these species to root rot.

DISTRIBUTION OF ROOT ROT

Root rot is a distinctly southwestern disease and is at present unknown outside of the area designated on the accompanying map (Figure 1). The exact limits of its occurrence are not at present accurately known but probably fall within the line on the map which designates the approximate area in which the soil and climatic conditions are favorable to the root-rot fungus.

The largest area of root-rot infection is found in a broad band running north and south and including about two thirds of the area of Texas (occurring to a greater or lesser extent in 196 of the 251 counties) and extending northward slightly over the state lines into Oklahoma (16) and Arkansas (18, 156) and southward

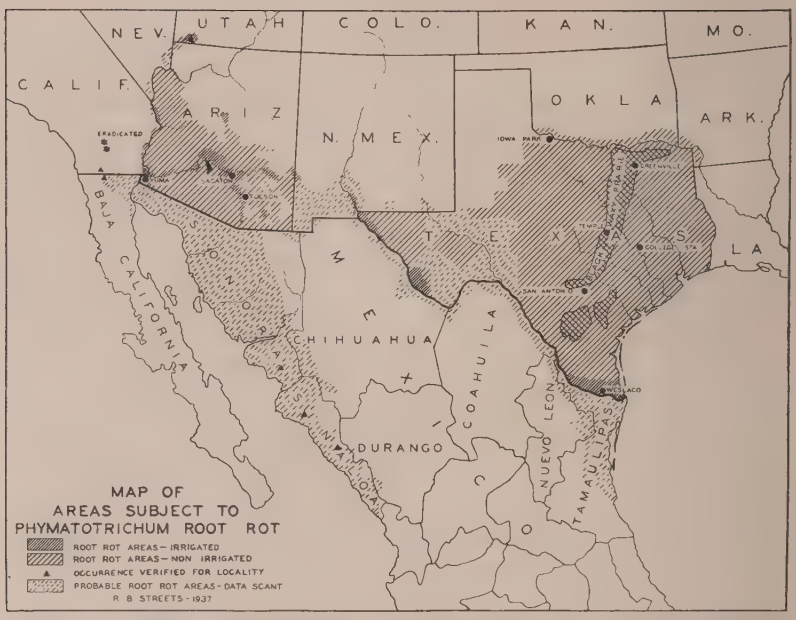

Figure 1.—Map of southwestern United States and northern Mexico showing present known distribution of Phymatotrichum root rot. Localities given show principal points in Arizona and Texas where root-rot investigations are under way. The Laguna district which grows a large per cent of the upland cotton produced in Mexico is not shown on the map as its exact location was not determined until after the map had been made. This district is an irregularly shaped valley of about 2,000 square miles in area surrounded by mountains. It is located on the boundary line of the states of Durango and Coahuila. Torreon is the principal city; altitude 4,000 feet; rainfall 6 to 8 inches making irrigation necessary; maximum temperatures 95 to 100 degrees F. in summer; minimum 24 degrees F. in winter. The climate is therefore similar to that of the other irrigated sections subject to root rot.

across the Rio Grande for an indefinite distance along the coastal plain of Mexico (139).[1]

The disease is likewise found in the irrigated sections along the Rio Grande and its tributaries in Texas and southern New Mexico and in southern Arizona and southward into the state of Sonora, Mexico (6b).[2] In 1930 King and Loomis (58) reported that the disease is known to exist in limited areas in the states of Baja California, Sonora, Chihuahua, and Coahuila in Mexico. Isolated natural infestations have been reported in the southeastern corner of Utah by Richards (103) and near Jacumba, California, by King (51) and Milbrath (74). That the disease is capable of thriving in parts of the Southwest where it has not been found to occur

[1] Reported from Tlahualilo, Durango.

[2] Reported on garbanzos from Rio Mayo, by J. G. Brown in 1922.

naturally has been proved repeatedly. Some years ago the disease was unwittingly introduced into the Coachella Valley with plants brought from infected areas, and the disease became established there necessitating a strenuous program of eradication to prevent its further spread (50, 71).

It is significant that the disease in its most destructive form is restricted to semiarid regions where the soils are definitely alkaline in reaction and also to regions of comparatively low altitude where the winter temperatures are not severe. The spread of the disease appears to be limited by natural barriers. On the west the strip of sand hills and desert mountain ranges have formed a barrier against the natural spread of root rot into Imperial and Coachella valleys. On the north low winter temperatures must be the limiting factor as favorable soils and host plants are found much farther north than the disease occurs. On the eastern border of the infected area the soils change from alkaline to very slightly alkaline and then to acid while temperature and moisture remain favorable. While very little definite information exists on the distribution of root rot in Old Mexico, it is known to occur at relatively low altitudes on both east and west coasts and adjoining Texas and Arizona, and it is not reported from the intervening highlands of the continental divide, so probably all factors—low winter temperatures, low rainfall, and acid soils—are limiting its southward spread.

Thus it appears that the root-rot fungus is well adapted to the alkaline soils, high temperatures, and low humidity of the Southwest but cannot withstand acid soils or freezing temperatures. It seems unlikely, therefore, that the disease will ever become a menace to crops in parts of the country east and north of its present distribution where soil and climatic conditions are unfavorable.

DISTRIBUTION IN ARIZONA

Root rot in Arizona is restricted to the southern half of the state, chiefly at altitudes below 4,000 feet (where cotton can be grown) (Figure 2). It is most prevalent and destructive in certain parts of the great irrigated valleys: the Yuma Valley, the Salt River Valley, the Santa Cruz, upper and lower Gila River valleys. Infected areas extend northward along the Colorado River to Blythe and Parker (71) and along the Verde River and Oak Creek to a point near Sedona. The disease is very irregular in distribution, some districts suffering severely every year, while others are almost entirely free from the disease.

OCCURRENCE ABROAD

Pathologists in several foreign countries have reported root diseases of cotton at first suspected of being Phymatotrichum root rot. Vasudeva (157) reports two root rots of cotton in India, the Punjab root rot due to *Rhizoctonia bataticola* in which sclerotia are rarely observed and the Gujerat root rot in which the sclerotia

Figure 2.—Map of Arizona showing areas subject to Phymatotrichum root rot.

of Rhizoctonia are found in abundance within the bark. Taubenhaus and Ezekiel (147e) conclude from microscopic examination and cultures of infected cotton roots from India that the Indian disease resembled alkali injury. They obtained *Sclerotium bataticola* and Fusarium in their cultures. Although Phymatotrichum root rot has been reported several times in the southern and southeastern districts of U.S.S.R., careful researches have failed to confirm these reports (14). So far as known, Phymatotrichum root rot does not at present occur outside the southwestern part of the United States and adjoining Mexico.

ORIGIN OF ROOT ROT

One of the questions most frequently asked concerning the disease is Where does root rot come from? The answer is that the root-rot fungus is indigenous to the arid Southwest throughout practically all of the region of its present known occurrence. It has been commonly observed that land cleared of native vegetation and planted to crops susceptible to root rot may become moderately or badly infected during the first years of cultivation. The appearance of root rot in a large area cleared and planted to cotton is reported by Peltier, King, and Samson (93) on a tract on the edge of the Salt River Valley. A similar condition was noted by the writer in the desert lands on the eastern edge of the Salt River Valley first cleared and irrigated in 1926 and 1927. The immediate appearance of root rot on susceptible crops when planted in virgin soils has also been reported by Taubenhaus, Dana, and Wolff (131) in Texas, King and Loomis (55) in Arizona, and Richards (103) in southwestern Utah. Wolff (155) reports finding infected wild plants and sclerotia on a railroad right of way that had not been under cultivation for at least forty years.

King and his associates (51, 53) have made a study of the occurrence of the root-rot fungus on Arizona desert vegetation. Following summer rains they found spore mats abundant in moist or shady spots along the highway crossing a high level plain separated from the general drainage channels and 12 miles from the nearest cultivated land. The roots of three species, rayless goldenrod (*Aplopappus heterophyllus*), wild hollyhock (*Sphaeralcea ambigua*), and a tiny prostrate spurge (*Chamaesyce albomarginata*) showed evidence of definite injury by the fungus. Typical strands of the root-rot fungus but no lesions or rotted tissues were found on the roots of mesquite (*Prosopis velutina*), desert buckthorn (*Condalia lycioides canescens*), and a slender jointed cholla (*Opuntia arbuscula*). One of three soil samples yielded two sclerotia of which one germinated.

In a second paper King, Hope, and Eaton (51) record finding the root-rot fungus on dead and dying plants of the Mexican poppy (*Argemone* sp.) near Jacumba, California. They also found the mycelium of the fungus on roots of Arizona sycamore (*Platanus wrightii*), the mesa paloverde (*Parkinsonia aculeata*), the blue paloverde of the desert washes (*Cercidium torreyanum*), spiny aster (*Aster spinosa*), broom weed (*Gutierrezia lucida*), a wild daisy (*Franseria confertifolia*), and the squawberry (*Lycium* sp.).

Rogers (106) reports the finding of native plants dying of root rot in both meadows and woodlands in Texas which have never been cultivated. Wolff (154, 155) found numerous spots of infection in a 400-acre meadow never cultivated in the blacklands, and seven species of native plants were commonly found infected.

Photo by J. G. Brown.

Plate III.—Umbrella trees killed by root rot in a city park. Note that the three small trees at the right also died as a result of being planted in infected soil.

ECONOMIC IMPORTANCE

Root rot is generally recognized as one of the most destructive plant diseases known and ranks as the most destructive disease of cotton in the United States (47, 139) in spite of the fact that it does not invade the large part of the cotton belt east of the state of Texas. Although root rot attacks more species of plants than any known fungus, the data concerning losses caused by the disease are restricted to cotton and a few other major crops. Not only field crops such as cotton, alfalfa, and other legumes but many garden and truck crops, and nearly all of the commonly cultivated deciduous fruit trees, nut trees, and small fruits, and a large proportion of our ornamental shade trees and shrubs, not to mention a considerable number of perennial and annual ornamental herbs and flowers are attacked by root rot, piling up a total annual loss from this disease which even as shown by the most conservative estimates is most impressive. Texas, because of her enormous acreage of cotton (from 11,000,000 to 19,000,000 acres per year) and the occurrence of root rot over perhaps two thirds the area of the state resulting in losses in all the susceptible plants grown in the root-rot area, has suffered much greater losses than other states. The average annual loss from root rot on all kinds of plants in Texas is estimated to be around $100,000,000 (135, 139), while a similar estimate for the seven other states in which the disease is found would add $50,000,000 to the annual toll (47).

LOSSES IN COTTON

Losses from root rot are greater in the case of cotton than for any other crop and have more than kept pace with the rapid in-

crease in acreage of cotton. Conservative estimates give the losses in Texas cotton alone as follows. 1887, $1,000,000; 1903, $2,000,000; 1906, $3,000,000. Figures for recent years are even more impressive.

In 1918, a dry year, Texas lost 5 per cent of the crop, or 130,000 bales valued at over $18,000,000 (December 1 price, 28 cents). In 1919, a wet year, the loss was 10 per cent of the crop or 314,000 bales worth $55,000,000 (December 1 price, 35 cents). In 1920, another wet year, the loss was 15 per cent or 630,000 bales, worth $41,000,000 at the low price of 13 cents which prevailed that year (148). The most complete and critical study of root-rot losses is the analysis of cotton losses for Texas in 1928 (26). The weighted average loss for the state was 8 per cent or 444,000 bales. This conservative estimate does not represent the average loss in root-rot districts, as nearly one third of the crop is grown in sections where root rot is unimportant. The weighted loss for root-rot sections was about 11 per cent.

In Arizona the losses are much less since the area under cultivation is also much smaller. The average loss for a period of six years (1924-29), however, was 10.3 per cent or approximately 10,000 bales each year. (See Table 1.) While varying considerably due to fluctuations in the price of cotton and amount of root rot from year to year, the annual loss to the cotton crop of Arizona is probably around $1,000,000 when the price is near 20 cents per pound.

TABLE 1.—LOSSES FROM PHYMATOTRICHUM ROOT ROT IN ARIZONA (PER CENT).

Crop	1924	1925	1926	1927	1928	1929	Average
Cotton	8	8	7.5	12	7	9	10.3
Alfalfa	3	3	2	4	1	3	2.5
Grape	..	3	1	2	1	1.5	1.7
Apple	4	4	1.5	2	3	1.5	3.3
Pear	2	2	1	1.5	2	2	1.75
Peach	4	1	3	2	3	2.5	2.6
Plum	3	1	1.5	2	1	2	1.75
Pepper tree	..	..	2	3	5	5	3.75

Data from Department of Plant Pathology, University of Arizona, and Plant Disease Survey, U.S. Department of Agriculture.

In addition to the reduction in amount of lint per acre, there is also additional loss from the lower quality of lint from plants killed by root rot and a reduction in amount and quality of cotton seed. Studies made in Texas (125, 142) showed that lint from plants killed more than three weeks before harvest graded one grade lower than that from healthy plants. There was also a reduction of 18 to 35 per cent in the fat content of cotton seeds from plants killed by root rot.

Plate IV.—Row of pepper trees planted in virgin soil. Tree at left is seventh in succession to die of root rot.

LOSSES IN ALFALFA AND OTHER FIELD CROPS

The per cent of loss in alfalfa for the same six years (1924-29) was lower than for cotton for several reasons: alfalfa is not so often planted in fields known to contain root rot, yields from early cuttings before root rot is active reduce the loss in yield, and not all alfalfa raising districts are seriously affected by root rot.

Much more serious than the estimated annual loss for alfalfa (2.5 per cent) is the fact that the susceptibility of all the commonly used leguminous field crops to root rot makes very difficult a practical soil building and soil conserving rotation to improve and maintain soil fertility as a basis for profitable agriculture. There seems to be no simple method of estimating these indirect losses, but they are nevertheless real.

LOSSES IN FRUIT TREES, NUT TREES, AND SMALL FRUITS

While the average number of fruit and nut trees of various kinds killed by root rot in Arizona each year varies from 2 to 5 per cent of the total number of trees, this figure represents only a fraction of the loss to the fruit industry of this state. Whenever root rot has appeared in an orchard, large or small, it has usually meant that the entire planting was doomed to succumb to the disease within a few years. Replanting to fill the gaps in the

rows proved futile as the new trees died about as rapidly as they were planted. The loss to the grower was usually complete, including the cost of five or more years' care bringing the orchard into production. Whether the control measures recently developed will prove adequate in controlling the disease in deciduous orchards remains to be seen. Plantings of grapes on infected soil suffer the fate of the fruit trees.

LOSSES IN GARDEN AND TRUCK CROPS

Since most of the summer-grown truck and garden crops are more or less susceptible to root rot, infected lands become of little value for truck farming. The heaviest direct losses from reduction in yield will be found in sweet potatoes, tomatoes, rhubarb, and okra. Root rot may prove a factor in the growing of sugar beet seed which has developed rapidly during the past two years, as the sugar beet is susceptible to root rot. Pyrethrum, another new crop now being tested, is likewise susceptible.

LOSSES IN SHADE TREES AND SHRUBS

A phase of root-rot losses which directly affects practically every individual, in regions where root rot occurs, who grows plants on any scale from a tiny dooryard to an elaborate, parklike estate is the fact that practically all of the taprooted ornamentals, both shade trees and shrubs, are susceptible to root rot—many of them very susceptible. In Arizona alone thousands of valuable shade trees and ornamentals valued at many thousands of dollars are killed each year by root rot. The problem is made more acute by the fact that trees and shrubs are usually planted close together for mass effects enabling the root-rot fungus to spread rapidly from plant to plant in its most destructive form. The growth of many of our otherwise most satisfactory trees and ornamentals becomes impracticable in soils known to be infected with root rot.

Plate V.—Fruitless mulberry slowly dying of root rot. Six healthy trees shown in background.

LOSSES IN ANNUAL AND PERENNIAL ORNAMENTALS AND FLOWERS

The losses in plants killed by root rot in the nonwoody annual and perennial ornamentals and flowers are less severe and of less consequence owing to the smaller value of the plants affected and

the large number of resistant and nonsusceptible species. Nevertheless centers of infection often spread from these plants to valuable shade trees and shrubs, so they may indirectly cause greater losses.

HOST RANGE

One of the most distinctive characteristics of the root-rot fungus is its ability to attack a very great number and variety of plants. Over 1,700 *species* of plants have been found susceptible—a record not equaled by any other bacterial or fungus plant parasite and approached only by the root-knot nematode (*Heterodera marioni* Cornu). There is ample evidence that this list is still incomplete and that perhaps several hundred more species will be added to the host list in the future. Following early lists of host plants by Heald and Wolff (39, 40, 41), several comprehensive lists have been issued giving the host plants for the state of Texas, beginning in 1923 with 169 susceptible species (148). A second list in 1929 included 274 cultivated species and 244 noncultivated plants and weeds, a total of 518 species (131, 141). The latest compilation (145) in 1936 shows 1,708 susceptible species in Texas.

This unusually large host list greatly increases the economic importance of root rot and multiplies the difficulties involved in controlling it. Satisfactory rotations with resistant crops, one of the most effective and practical methods of controlling root-invading fungi, are especially difficult to arrange in the case of root rot.

The lists of host plants compiled from Texas are not entirely adapted for use in Arizona for they contain many species not planted or native to Arizona, and this state has a considerable number of species not grown in Texas. Likewise the degree of susceptibility of some species is different in Arizona than reported from Texas, probably due to different environmental conditions or to different strains of the root-rot fungus.

Since a single alphabetical list of plants susceptible to root rot has been found inconvenient to use, the list has been made according to the type of planting as follows:

Table 2.—Principal host plants of the root-rot fungus in Arizona (very general and not complete).
Table 3.—Relative susceptibility of field crops.
Table 4.—Garden and truck crops.
Table 5.—Fruit trees, nut trees, and small fruits.
Table 6.—Shade trees.
Table 7.—Shrubs, vines, and other woody ornamentals.
Table 8.—Perennial flowers and bulbs.
Table 9.—Annual flowers.
Table 10.—Weeds.
Table 11.—Woody plants not commonly cultivated.
Table 12.—Noncultivated plants.

In compiling these tables all plants not cultivated in the parts

of Arizona subject to root rot were eliminated[3] and the classification of degree of susceptibility is based largely upon our own observations since 1925. The plants are listed arbitrarily in four classes or degrees of susceptibility and although this is admitted to be only an approximate grouping, it has been used by us for years and has been found very useful.[4] Additions and changes have been made in our lists every year and will continue to be made as more data are secured.

Plants in the "very susceptible" group (and the "moderately susceptible" group) should be avoided where root rot is known to be present in the soil.

TABLE 2.—PRINCIPAL HOST PLANTS OF THE ROOT-ROT FUNGUS IN ARIZONA.

Field and truck crops	Tree fruits and small fruits	Ornamentals, trees	Ornamentals, shrubs, and flowers
Alfalfa	Pome fruits	Shade trees	Privets
Beets and sugar beets	Apple	Umbrella tree	Euonymous, Jap.
	Pear	Chinese elm	Roses
Cotton	Quince	Pepper tree	Virginia creeper
Cowpeas	Stone fruits	Bottle tree	Hollyhock
Okra	Peach	Cottonwoods	Four-o'clock
Soybeans	Apricot	Poplars	Castor bean
Sweet potatoes	Plum	Black locust	
Tomatoes	Almond	Pistache	
	Fig	Mulberry	
	Jujube	Pecan	
	Grapes		

Plants listed as "slightly susceptible" should be chosen for planting in regions where root rot is common in preference to more susceptible plants. In addition to being much less damaged by root rot they can often be protected against root rot or cured by treatment. Slightly susceptible plants should not be used, however, as replants in infected soil during a program designed to eradicate root rot.

Plants listed as "immune" should be used exclusively on infected land whenever possible, although the list of immune plants is somewhat limited. The only group of plants which has proved to be consistently and entirely immune is the monocotyledons (plants with parallel veins and fibrous root systems). The most important plants of this group in cultivation belong to the grass, sedge, palm, cycad, lily, amaryllis, iris, and orchid families.

[3] Thanks are due to Professor J. J. Thornber, Botanist of the Experiment Station, for checking plant lists for Arizona grown species, and for verifying the botanical names used.

[4] The tables in this bulletin had been completed when the most recent Texas list (145) was published. Comparison reveals close agreement on method of rating degree of susceptibility except that the Texas publication splits the most susceptible group into two, "extremely susceptible" and "very susceptible," a distinction which it seems unnecessary to follow in this bulletin.

Definite resistance is likewise shown by members of the melon, mint, myrtle, tamarisk, citrus, honeysuckle, and verbena families, although some species of these families are more or less susceptible. Plants belonging to other than the monocotyledon group should not be listed as entirely immune to root rot until they have been extensively tested under a variety of conditions, as species commonly grown in Arizona in root-rot areas have developed root rot after appearing immune during a period of observation extending as long as ten years. In some cases seedlings of a species considered highly resistant will succumb to root rot where no record of injury to older established plants is known.

In general, members of the large group of dicotyledons (tap-rooted plants) are more or less susceptible, especially members of the cotton, legume, morning glory, rose, pome, drupe, elm, and poplar families.

In several of the tables will be found groups of susceptible plants which escape injury from root rot by being grown during the period when the root-rot fungus is relatively inactive. These crops, planted in the fall, mature in winter or early spring before the soil temperatures are favorable for root-rot activity. It is not definitely known whether the root-rot fungus attacks the root systems of these plants or is able to obtain nourishment from them before or after the early harvest. If these winter-annual crops furnish nourishment for the fungus they should not be used in eradication programs.

In preparing the tables, the host plants have been listed alphabetically under each degree of susceptibility. The common name is given in the first column and the botanical name in the second column to avoid any possible confusion as to identity of the species. This is especially necessary in the case of the newer and little known crop and ornamental plants, weeds, and native plants.

Some plants not well-known or commonly grown in Arizona are included in the tables, as they are either under experimental tests to determine their local value or are known to be established in the root-rot areas.

SUSCEPTIBILITY OF FIELD CROPS

Table 3 gives the relative susceptibility of the field crops and crops grown as green manure and cover crops in orchards. It will be noted that nearly all of the leguminous crops are moderately or very susceptible, and that the immune crops are the cereals, sorghums, and grasses.

SUSCEPTIBILITY OF GARDEN AND TRUCK CROPS

Table 4 shows that nearly all of the summer grown garden and truck crops are susceptible to root rot, while winter grown truck crops escape injury. Carrots, lettuce, and spinach have been found quite susceptible in summer. The only entirely immune vegetables are onions, garlic, and asparagus (monocotyledons).

TABLE 3.—RELATIVE SUSCEPTIBILITY OF FIELD CROPS TO ROOT ROT.[1]

Susceptibility	Crop	Botanical name
Very susceptible	*Alfalfa	*Medicago sativa* L.
	*Bean, tepary	*Phaseolus acutifolius* A. Gray var. *latifolius* Freem.
	*Cotton, Pima	*Gossypium barbadense* L.
	*Cotton, upland	*Gossypium hirsutum* L.
	*Cowpea	*Vigna sinensis* Endl.
	Hemp, common	*Cannabis sativa* L.
	*Soybean	*Soja max* Piper
	*Sugar beet	*Beta vulgaris* L.
	Sweet clover, annual yellow	*Melilotus indica* All.
	*Sweet clover, biennial yellow	*Melilotus officinalis* Lam.
	Sweet clover, Hubam	*Melilotus alba* Desr. var. *annua* Coe.
	*Sweet clover, white	*Melilotus alba* L.
Moderately susceptible	Bean, mung	*Phaseolus aureus* Roxb.
	Guayule	*Parthenium argentatum* Gray
	Pyrethrum	*Chrysanthemum cinerariaefolium* Viz.
	Velvet bean, bush	*Stizolobium* sp.
Slightly susceptible	†Cowpea, Brabham	*Vigna sinensis* Endl.
	†Cowpea, iron	*Vigna sinensis* Endl.
	Crotalaria	*Crotalaria incana* L.
	Crotalaria	*Crotalaria juncea* L.
	Guar	*Cyamopsis tetragonoloba* (L.) Taub.
	Sesame	*Sesamum orientale* L.
	*Sesbania, common	*Sesbania macrocarpa* Muhl.
	Sesbania, red stem	*Sesbania cannabina* (Retz.) Poir.
Winter grown crops which escape root-rot injury[2]	†Flax	*Linum usitatissimum* L.
	†Kale	*Brassica oleracea* L. var. *acephala* DC.
	†Mustard, black	*Brassica nigra* Koch
	†Mustard, white	*Brassica alba* Boiss.
	†Rape	*Brassica napus* L.
	†Sweet clover, annual yellow	*Melilotus indica* All.
	†Sweet clover, Hubam	*Melilotus alba* Desr. var *annua* Coe.

[1] Where symbol *, †, ‡, or § precedes name in tables 3, 4, 5, 6, 7, 8, and 9, susceptibility rating is based on Arizona data and experience. Where definite data are lacking or insufficient, no symbol is used and rating is taken from latest revised Texas list (Bull. 527, 1936), and other sources.

* Recorded susceptible in Arizona and Texas.

† First recorded susceptible in Arizona (usually not in other lists).

‡ Rating given here differs from published rating.

§ Untried in Arizona.

[2] These susceptible crops planted in the fall for winter or early spring harvest are not injured by root rot.

TABLE 3.—RELATIVE SUSCEPTIBILITY OF FIELD CROPS TO ROOT ROT[1]—*Continued.*

Susceptibility	Crop	Botanical Name
Immune	*Corn	*Zea mays* L.
	Small grains	
	*Barley	*Hordeum vulgare* L.
	*Oats	*Avena sativa* L.
	*Rye	*Secale cereale* L.
	*Wheat	*Triticum aestivum* L.
	*Sorghums (milo, amber, etc.)	*Holcus sorghum* L.
	Millet	*Chaetochloa italica* (L.) Scribn.
	All grasses, including	
	*Bermuda grass	*Cynodon dactylon* Pers.
	*Johnson grass	*Holcus halepensis* L.
	*Sudan grass	*Holcus sudanensis* Bailey

TABLE 4.—RELATIVE SUSCEPTIBILITY OF GARDEN AND TRUCK CROPS TO ROOT ROT.[1]

Susceptibility	Crop	Botanical name
Very susceptible (when summer grown)	Artichoke, Jerusalem	*Helianthus tuberosus* L.
	Beans, snap or dry	*Phaseolus vulgaris* L.
	*Beets, common garden	*Beta vulgaris* L.
	Carrot	*Daucus carota* L.
	Dill	*Anthemum graveoleus* L.
	Horse-radish	*Radicula armoracia* Rob.
	*Okra	*Hibiscus esculentus* L.
	Parsnip	*Pastinaca sativa* L.
	*Peanut	*Arachis hypogaea* L.
	*Pepper	*Capsicum annuum* L.
	*Rhubarb	*Rheum rhaponticum* L.
	Roselle (rare)	*Hibiscus sabdariffa* L.
	*Sweet potato	*Ipomoea batatis* Lam.
	Vegetable oyster	*Tragopogon porrifolius* L.
Moderately susceptible	Artichoke, globe	*Cynara scolymus* L.
	*Eggplant	*Solanum melogena* L.
	†Garbanzo (chick-pea)	*Cicer arietinum* L.
	†Potato, white (Irish)	*Solanum tuberosum* L.
	Squash, summer crookneck	*Cucurbita pepo* L. var. *condensa* Bailey
	‡Tomato	*Lycopersicon esculentum* Mill.
	†Watermelon	*Citrullus vulgaris* L.
Slightly susceptible or immune	Melon family	
	*Cantaloupe	*Cucumis melo* L.
	†Cassaba	*Cucumis melo* L. var. *inodorata*
	Cucumber	*Cucumis sativus* L.
	*Cushaw	*Cucurbita moschata* Duchesne
	*Muskmelon	*Cucumis melo* L.
	*Pumpkin	*Cucurbita pepo* L.
	*Squash	*Cucurbita maxima* Duchesne

[1] For explanation of symbols, see footnote under Table 3.

TABLE 4.—RELATIVE SUSCEPTIBILITY OF GARDEN AND TRUCK CROPS TO ROOT ROT[1]—*Continued.*

Susceptibility	Crop	Botanical Name
Winter grown vegetables which escape root-rot injury	*Beet, common garden	*Beta vulgaris* L.
	*Carrot	*Daucus carota* L.
	Chard, Swiss	*Beta vulgaris* L. var. *cicla* L.
	*Lettuce	*Lactuca sativa* L.
	Mustard family	
	Broccoli	*Brassica oleracea* L. var. *botrytis* L.
	Brussels sprouts	*Brassica oleracea* L. var. *gemmifera* Zenker
	*Cabbage	*Brassica oleracea* L. var. *capitata* L.
	*Cauliflower	*Brassica oleracea* L. var. *botrytis* L.
	Kohlrabi	*Brassica oleracea* L. var. *caulorapa* Pasq.
	Mustard greens	*Brassica japonica* Hort.
	Radish	*Raphanus sativus* L.
	Rutabaga	*Brassica oleracea* L. var. *napobrassica* L.
	Turnip	*Brassica rapa* L.
	Parsley	*Petroselinum hortense* Hoffm.
	*Peas	*Pisum sativum* L.
	*Spinach	*Spinacea oleracea* L.
Immune	*Asparagus	*Asparagus officinalis* L.
	*Garlic	*Allium sativum* L.
	*Onion	*Allium cepa* L.

SUSCEPTIBILITY OF FRUIT TREES, NUT TREES, AND SMALL FRUITS

Table 5 covers a diverse group, but the plants listed, with the exception of the small fruits, are mostly long-lived trees, and root-rot injury in such orchard plantings is of great economic importance. Deciduous fruits, with the exception of the pomegranate, are very susceptible. The subtropical fruits, with the exception of citrus and dates, are susceptible, while the nut-bearing trees are moderately susceptible. Since nearly all Arizona citrus is grown on the sour orange rootstock, which is highly resistant, citrus crops escape injury.

TABLE 5.—RELATIVE SUSCEPTIBILITY OF FRUIT TREES, NUT TREES, AND SMALL FRUITS TO ROOT ROT.[1]

Susceptibility	Crop	Botanical name
Very susceptible	Avacado (rare)	*Persea gratissima* Gaertn. f.
	*Fig	*Ficus carica* L.
	*Grapes, American	*Vitis labrusca* L. and hybrids
	*Grapes, European	*Vitis vinifera* L.

[1] For explanation of symbols, see footnote under Table 3.

TABLE 5.—RELATIVE SUSCEPTIBILITY OF FRUIT TREES, NUT TREES, AND SMALL FRUITS TO ROOT ROT[1]—*Continued.*

Susceptibility	Crop	Botanical Name
Very susceptible	*Jujube (Chinese date)	*Zizyphus jujuba* Mill.
	Persimmon, Kaki (Japanese)	*Diospyros kaki* L. f.
	*Pistache	*Pistacia vera* L.
	Pome fruits	
	*Apple	*Pyrus malus* L.
	*Pear	*Pyrus communis* L.
	Quince	*Cydonia vulgaris* Mill.
	Stone fruits	
	*Almond	*Prunus communis* Fritsch.
	*Apricot	*Prunus armeniaca* L.
	*Peach	*Amygdalus persica* L.
Moderately susceptible	†Blackberry	*Rubus* sp.
	†Blackberry, evergreen thornless	*Rubus ulmifolius* Schott. var. *inermis* Foche
	Citron	*Citrus medica* L.
	*Currant, red	*Ribes vulgare* Lam.
	†Loganberry	*Rubus loganobaccus* Bailey
	*Olive	*Olea europaea* L.
	*Pecan	*Carya pecan* Aschers. and Graebn.
	Persimmon, common	*Diospyros virginiana* L.
	Plum, American	*Prunus americana* Marsh.
	*Plum, common	*Prunus domestica* L.
	Raspberry, red	*Rubus strigosus* Michx. var. *idaeus* L.
	*Tung-oil tree (rare)	*Aleurites fordii* Hemsl.
	Walnut, black	*Juglans nigra* L.
	†Walnut, Calif. black	*Juglans californica* S. Wats.
	Walnut, English	*Juglans regia* L.
	Walnut, Japanese (rare)	*Juglans sieboldiana* Maxim.
Slightly susceptible	*Citrus fruits on sour-orange root (orange, lemon, grapefruit, lime, etc.)	*Citrus aurantium* L.
	*Currant, black	*Ribes americanum* Mill.
	Orange, hardy	*Poncirus (Citrus) trifoliata* (L.) Raf.
	*Pomegranate	*Punica granatum* L.
Immune	*Date palm	*Phoenix dactylifera* L.
	*Strawberry	*Fragaria chiloensis* Duchesne

SUSCEPTIBILITY OF SHADE TREES

Table 6 includes the shade trees, both deciduous and evergreen. It is worthy of notice that the fruit, nut, and shade trees have the highest percentage of very susceptible species of any groups of plants. Many of the shade trees most extensively planted in Arizona are in the very susceptible group, and many more are in

Plate VI.—Seedling trees of Osage orange showing some plants of this resistant species killed by root rot.

the moderately susceptible group. The only group of entirely immune shade trees is the palms, although root rot has rarely been found on species of eucalyptus grown here. The coniferous evergreens (cypresses, pines, etc.) belong mostly in the slightly susceptible group as they are rarely killed by root rot. The evergreen and deciduous species of tamarisk are likewise highly resistant.

TABLE 6.—RELATIVE SUSCEPTIBILITY OF SHADE TREES TO ROOT ROT.[1]

Susceptibility	Plant	Botanical name
Very susceptible	†Bottle tree	*Sterculia diversifolia* Don.
	†Carob	*Ceratonia siliqua* L.
	*Chinaberry tree	*Melia azedarach* L.
	†Cottonwood, Arizona	*Populus arizonica* Sargent
	†Cottonwood, MacDougal's	*Populus macdougallii* Rose
	*Cottonwood, southern	*Populus deltoides* Marsh.
	†Cottonwood, Thornber	*Populus fremontii* Wats. var. *thornberi* Sarg.
	Elm, American	*Ulmus americana* L.
	*Elm, Chinese	*Ulmus pumila* L.

[1] For explanation of symbols, see footnote under Table 3.

TABLE 6.—RELATIVE SUSCEPTIBILITY OF SHADE TREES TO ROOT ROT[1]—*Continued.*

Susceptibility	Plant	Botanical Name
Very susceptible	Elm, evergreen (rare)	*Ulmus parvifolia* Jacq.
	*Locust, black	*Robinia pseudoacacia* L.
	*Locust, honey	*Gleditsia triancanthos* L.
	Maidenhair tree (rare)	*Ginkgo biloba* L.
	Mulberry, paper (rare)	*Broussonetia papyrifera* (L.) Vent.
	‡Pepper tree	*Schinus molle* L.
	‡Pepper tree, Brazilian	*Schinus terebinthifolius* Raddi.
	Pistache, Chinese	*Pistachia chinensis* Bunge
	†Poplar, Bolle's	*Populus alba* var. *pyramidalis* Bunge
	*Poplar, Carolina	*Populus eugenei* Simon-Lewis
	†Poplar, Jack's	*Populus jackii*
	*Poplar, Lombardy	*Populus nigra* L. var. *italica* Du Roi
	Tallow tree, Chinese (rare)	*Sapium sebiferum* (L.) Roxb.
	*Tree of heaven	*Ailanthus altissima* Swingle
	*Umbrella tree, Texas	*Melia azedarach* L. var. *umbraculiformis* Berck.
	*Willow, weeping	*Salix babylonica* L.
	*Willow, black	*Salix nigra* L.
Moderately susceptible	Ash, green	*Fraxinus lanceolata* Borck.
	†Beefwood	*Casuarina cunninghamiana* Mig.
	Box elder	*Acer negundo* L.
	†Box elder, western	*Acer interior* Britton
	Camphor tree (rare)	*Cinnamomum camphora* Nees. & Eberm.
	‡Catalpa, western	*Catalpa speciosa* Warder
	Cherry laurel	*Prunus caroliniana* Ait.
	Jacaranda tree	*Jacaranda mimosaefolia* D. Don.
	Maple, sycamore	*Acer pseudoplatanus* L.
	Magnolia, southern (rare)	*Magnolia grandiflora* L.
	†Mulberry, fruitless	(Rootstock) *Morus alba* L.
	‡Mulberry, Russian	*Morus alba* L. var. *tartarica* Loudon
	†Oak, cork	*Quercus suber* L.
	‡Olive	*Olea europaea* L.
	Plane tree, European	*Platanus orientalis* L.
	Privet, glossy	*Ligustrum lucidum* Ait.
	*Silk oak	*Grevillea robusta* Cunn.
	*Walnut, black	*Juglans nigra* L.
Slightly susceptible	†Ash, Arizona	*Fraxinus velutina* var. *Toumeyi* Rehd.
	‡Bagote (seedlings susceptible)	*Parkinsonia aculeata* L.
	†Calomondin	*Citrus mitis* Blanco
	‡Cypress, Arizona	*Cupressus arizonica* Greene
	‡Cypress, Italian	*Cupressus sempervirens* L.
	‡Cypress, Monterey	*Cupressus macrocarpa* Hartw.
	§Elm, cedar	*Ulmus crassifolia* Nutt.
	†Eucalyptus, desert gum	*Eucalyptus rudis* Endl.

TABLE 6.—RELATIVE SUSCEPTIBILITY OF SHADE TREES TO ROOT ROT[1]—*Continued.*

Susceptibility	Plant	Botanical name
Slightly susceptible	†Eucalyptus (misc.)	*Eucalyptus* spp.
	†Eucalyptus, red box	*Eucalyptus polyanthema* Schauer.
	†Eucalyptus, red gum	*Eucalyptus rostrata* Schlecht.
	Hackberry	*Celtis occidentalis* L.
	Kentucky coffee tree	*Gymnocladus dioica* (L.) Koch
	*Orange, hardy	*Poncirus* (=*Citrus*) *trifoliata* (L.) Raf.
	*Orange, sour (Seville)	*Citrus aurantium* L.
	*Osage orange	*Maclura pomifera* Schneid.
	*Plane tree, American	*Platanus occidentalis* L.
	Scholar's tree, Chinese (rare)	*Sophora japonica* L.
	†Sycamore, Arizona	*Platanus wrightii* S. Wats.
	‡Tamarisk, evergreen (Athel)	*Tamarix articulata* Vahl.
	‡Tamarisk, pink flowered	*Tamarix gallica* L.
	†Walnut, native black	*Juglans major* Heller
Immune	Palms, all species including	
	†Palm, blue	*Erythea armata* S. Wats.
	*Palm, canary	*Phoenix canariensis* Chaub.
	*Palm, date	*Phoenix dactylifera* L.
	*Palm, California fan	*Washingtonia filifera* Wendl.
	*Palm, slender fan	*Washingtonia robusta* Parish.
	†Palm, Chinese windmill	*Trachycarpus excelsa* H. Wendl.
	‡Paloverde, blue	*Cercidium torreyanum* Sargent

SUSCEPTIBILITY OF SHRUBS, VINES, AND OTHER WOODY ORNAMENTALS

Table 7 lists a diverse group of large and small shrubs, vines, and other woody ornamentals. Many of the shrubs most extensively planted in Arizona, including privets, roses, cotoneaster, and buddleia, are susceptible. The coniferous evergreens (arborvitae, junipers, etc.), oleander, pyracanthas, and jasmines possess considerable resistance. The immune group consists mainly of monocotyledons and native plants such as desert willow and Arizona elderberry.

SUSCEPTIBILITY OF PERENNIAL FLOWERS, ETC.

Table 8 includes perennial flowers, vines with perennial roots, and plants propagated by bulbs, corms, and fleshy rhizomes. Only hollyhocks and four-o'clocks are listed as very susceptible, but eight species are moderately susceptible. Members of the mint family show a high degree of resistance. The immune group in-

Plate VII.—Root systems of seedling Arizona ash (*A*) and Osage orange (*B*) showing infection by the root-rot fungus. Seed planted in spring; photographed October 25.

cludes monocotyledons such as the flowering bulbs, iris, cannas, and lilies. In general, ferns, swamp and aquatic plants are immune to root rot.

SUSCEPTIBILITY OF ANNUAL FLOWERS

Table 9 lists the susceptibility of plants usually grown as annuals, although some of them may live several years in our climate. None are very susceptible to root rot, although some are moderately susceptible. Since a large proportion of our flowers are grown as winter annuals, root rot is less of a problem in the flower garden than in the case of trees or shrubs, as the flowers

escape injury. Fortunately, the most extensively grown summer flowers, zinnias and marigolds, and in addition strawflowers and cultivated amaranths are not injured by root rot.

TABLE 7.—RELATIVE SUSCEPTIBILITY OF SHRUBS, VINES, AND OTHER WOODY ORNAMENTALS TO ROOT ROT.[1]

Susceptibility	Plant	Botanical name
Very susceptible	†Broom, Spanish	*Spartium junceum* L.
	*Castor bean	*Ricinus communis* L.
	*Cotoneaster, silverleaf	*Cotoneaster pannosa* French
	‡Euonymous, Japanese	*Euonymus japonicus* Lf.
	Lilac, Chinese	*Syringa chinensis* Willd.
	Lilac, common	*Syringa vulgaris* L.
	*Lilac, Persian	*Syringa persica* L.
	Photinia, Chinese	*Photinia serrulata* Lindl.
	Poinsettia	*Poinsettia pulcherrima* Graham
	*Privet, Amur	*Ligustrum amurense* Carr.
	*Privet, Chinese	*Ligustrum sinense* Lour.
	Quince, flowering Jap.	*Cydonia japonica* Pers.
	Redbud, California	*Cercis occidentalis* Torr.
	*Redbud, Chinese	*Cercis chinensis* Bunge
	*Roses, cult. varieties	Rootstock—*Rosa odorata* Sweet.
	*Roses, cult. varieties	Rootstock—*Rosa multiflora* Thunb.
	*Roses, cult. varieties	On own roots
	*Silverberry	*Eleagnus argentea* Pursh.
	Spirea	*Spirea vanhouttei* Zabel
Moderately susceptible	Abelia (rare)	*Abelia grandiflora* Rend.
	‡Acacia, bald	*Acacia neriifolia* Cunn.
	†Acacia, weeping	*Acacia pendula* Cunn.
	Barberry, Japanese	*Berberis thunbergii* DC.
	†Bird of paradise	*Poinciana gilliesii* Wall.
	†Bottle brush	*Callistemon rigidus* R. Br.
	†Butterfly bush, Lilac	*Buddleia davidi* French.
	Butterfly bush, white	*Buddleia asiatica* Lour.
	*Cape honeysuckle	*Tecoma capensis* Voss
	†Cassia (senna)	*Cassia artemisoides* Gand.
	*Chaste tree, lilac	*Vitex angus-castus* L.
	*Ivy, English	*Hedera helix* L.
	Leucophyllum (rare)	*Leucophyllum texanum* Benth.
	‡Nandina	*Nandina domestica* Thunb.
	Passionflower, blue	*Passiflora caerulea* L.
	*Pittosporum, Japanese	*Pittosporum tobira* Ait.
	*Privet, California	*Ligustrum ovalifolium* Hassk.
	*Privet, Japanese	*Ligustrum japonicum* Thunb.
	Privet, Nepal (rare)	*Ligustrum nepalense* Wall.
	‡Trumpet vine, cat's-claw	*Bignonia tweediana* Lindl. (= *Doxantha unguis-cati* Redh.)
	*Virginia creeper	*Ampelopsis quinquefolia* Michx.
	Wisteria, Japanese	*Wisteria floribunda* DC.

[1] For explanation of symbols, see footnote under Table 3.

TABLE 7.—RELATIVE SUSCEPTIBILITY OF SHRUBS, VINES, AND OTHER WOODY ORNAMENTALS TO ROOT ROT[1]—*Continued.*

Susceptibility	Plant	Botanical name
Slightly susceptible or immune	‡Arborvitae, Oriental (many cult. varieties)	*Thuja orientalis* L.
	‡Cactus, many species	*Opuntia* spp. et al.
	Cedar, red	*Juniperus virginiana* L.
	†Coral vine (Rosa de Montaña, queen's wreath)	*Antigonon leptopus* Hook. & Am.
	‡Crape myrtle	*Lagerstroemia indica* L.
	†Feijoa	*Feijoa sellowiana* Berg.
	‡Honeysuckle, evergreen	*Lonicera japonica* Thunb.
	Indigo plant (rare)	*Amorpha fruticosa* L.
	†Jasmine	*Jasminum floridum* Bunge
	‡Jasmine, Chinese (bush)	*Jasminum primulinum* Hemsl.
	‡Jasmine, Italian	*Jasminum humile* L. (= *J. revolutum* Sims)
	†Jasmine, Spanish (white flowered)	*Jasminum grandiflorum* L.
	*Juniper, alligator	*Juniperus pachyphloea*
	*Juniper, Pfitzer	*Juniperus chinensis* L. var. *pfitzeriana* Spaeth.
	*Juniper, Rocky Mt.	*Juniperus scopulorum* Sarg.
	†Myrtle, dwarf	*Myrtis communis* var. *compacta*
	‡Myrtle, Roman	*Myrtis communis* L.
	†Myrtle, small-leafed	*Myrtis communis* var. *microphylla* Hort.
	‡Oleander	*Nerium oleander* L.
	†Pyracantha (common)	*Pyracantha crenulata* Roem.
	†Pyracantha (orange-yellow berries)	*Pyracantha angustifolia* Schneid.
	‡Pyracantha (orange-red berries)	*Pyracantha coccinea* Roem. var. *lalandii* Dipp.
	†Pyracantha (red berries)	*Pyracantha gibbsii* A. B. Jacks. var. *yunnanensis* Osborn
	†Pyracantha (red berries)	*Pyracantha formosana*
	*Russian olive	*Eleagnus angustifolia* L.
	*Siberian pea tree	*Caragana arborescens* Lam.
Very resistant or immune	Acacia, sweet	*Acacia farnesiana* Willd.
	*Bamboo, cult. vars.	*Bambusa* spp.
	Banana, Abyssinian	*Musa ensete* Gmel.
	Breath-of-heaven (rare)	*Diosma ericoides* L.
	*Century plant	*Agave americana* L.
	‡Desert willow[2]	*Chilopsis linearis* DC.
	Dracaena palm	*Cordaline australis* Hook.
	†Elderberry, Arizona blue	*Sambucus coerulea* var. *arizonica* Sarg.

[2] This plant is listed as "very susceptible" in Texas (145). No plants were found infected in a 1-acre nursery planting at Tucson in 1935. A critical examination of roots from Chilopsis bordering on root-rot spot in Chinese elm nursery rows revealed no sign of infection.

TABLE 7.—RELATIVE SUSCEPTIBILITY OF SHRUBS, VINES, AND OTHER WOODY ORNAMENTALS TO ROOT ROT[1]—*Continued.*

Susceptibility	Plant	Botanical name
Very resistant or immune	*Flax, New Zealand	*Phormium tenax* Forst.
	Hibiscus, Turk's cap (seedlings not immune)	*Malvaviscus Conzattii* Greenm.
	*Pampas grass	*Cortaderia argentea* Stepf.
	‡Pomegranate, com. & D. F.	*Punica granatum* L.
	†Pomegranate, dwarf evergreen	*Punica granatum* var. *nana* Hort.
	*Reed, giant ("bamboo")	*Arundo donax* L.
	*Rosemary	*Rosemarinus officinalis* L.
	*Sotol	*Dasylirion wheeleri* S. Wats.
	*Spanish bayonet	*Yucca aloifolia* L.
	Yucca, drooping	*Yucca recurvifolia* Salisb.

TABLE 8.—RELATIVE SUSCEPTIBILITY OF PERENNIAL FLOWERS AND BULBS TO ROOT ROT.[1]

Susceptibility	Plant	Botanical name
Very susceptible	*Dahlia	*Dahlia rosea* Cav.
	*Four-o'clock	*Mirabilis jalapa* L.
	*Hollyhock, common	*Althaea rosea* Cav.
	Hollyhock, figleaf	*Althaea ficifolia* Cav.
Moderately susceptible	Baloon vine	*Cardiospermum halicacabum* L.
	Bean, hyacinth	*Dolochis lablab* L.
	‡Chrysanthemum, hardy	*Crysanthemum morifolium* Ram.
	‡Clover, white Dutch	*Trifolium repens* L.
	Daisy, Shasta	*Chrysanthemum maximum* Ram.
	‡Gaillardia, perennial	*Gaillardia aristata* Pursh.
	Kudzu vine	*Pueraria thunbergiana* Benth.
	*Lantana, common	*Lantana camara* L.
	Madeira (mignonette) vine	*Boussingaultia baselloides* H. B. K.
	Moonflower (vine)	*Calonyction aculeatum* (L.) House
	Sundrops, rose	*Oenothera rosea* Ait.
Slightly susceptible	Carnation	*Dianthus caryophyllus* L.
	Columbine, American	*Aquilegia canadensis* L.
	*Lantana, trailing	*Lantana sellowiana* Link. & Otto.
	Lavender	*Lavendula spicata* L.
	Lippia	*Lippia canescens* H. B. K.
	Sage, garden	*Salvia officinalis* L.
Immune	Baby's breath	*Gypsophila paniculata* L.
	*Catnip	*Nepeta cataria* L.
	Geranium	*Pelargonium* spp.
	Hoarhound, common	*Marrubium vulgare* L.

[1] For explanation of symbols, see footnote under Table 3.

TABLE 8.—RELATIVE SUSCEPTIBILITY OF PERENNIAL FLOWERS AND BULBS TO ROOT ROT[1]—*Continued.*

Susceptibility	Plant	Botanical name
Immune	Mint, round-leafed	*Mentha rotundifolia* Huds.
	Oxalis, rose	*Oxalis rubra* St. Hil.
	*Periwinkle, rose	*Vinca rosea* L.
	*Periwinkle (vinca)	*Vinca major* L.
	Sage, azure	*Salvia azurea* Lam.
	Sage, mealy-cup	*Salvia farinacea* Benth.
	Spearmint	*Mentha spicata* L.
	*Violet	*Viola odorata* L.
	Monocotyledons including	
	Amaryllis	*Amaryllis* spp.
	Calla, golden	*Zantedeschia elliottiana* Engler
	*Calla, white	*Zantedeschia aethiopica* Spreng.
	*Canna	*Canna indica* L.
	*Crinum	*Crinum* spp.
	*Crocus	*Crocus* spp.
	*Gladiolus	*Gladiolus* spp.
	*Hyacinth	*Hyacinthus orientalis* L.
	Iris, blueflag	*Iris versicolor* L.
	*Iris, cult. varieties	*Iris germanica* et al.
	Lily, Chinese sacred	*Narcissus tazetta* L. var. *orientalis* Hort.
	Lily, Easter	*Lilium longiflorum* Thunb.
	*Narcissus	*Narcissus jonquilla* L.
	Papyrus, Egyptian	*Cyperus papyrus* L.
	Tuberose	*Polianthes tuberosa* L.
	*Tulip	*Tulipa gesneriana* L.
	*Umbrella plant	*Cyperus alternifolius* L.
	Aquatic plants in gen.	
	Bulb & corm plants in general	
	Ferns in general	
	Swamp plants in gen.	

TABLE 9.—RELATIVE SUSCEPTIBILITY OF ANNUAL FLOWERS, VINES, ETC. TO ROOT ROT.[1]

Susceptibility	Plant	Botanical name
Very susceptible		
Moderately susceptible	California poppy	*Eschscholtzia californica* Cham.
	Calliopsis	*Coreopsis tinctoria* Nutt.
	Cosmos, common	*Cosmos bipinnatus* Cav.
	‡Cosmos, yellow	*Cosmos sulphureus* Cav.
	Cornflower	*Centaurea cyaneus* L.
	Morning-glory, bush	*Ipomoea leptophylla* Garr.
	*Morning-glory, common	*Ipomoea purpurea* Lam.
	Morning-glory, ivy-leaf	*Ipomoea hederacea* Jacq.

[1] For explanation of symbols, see footnote under Table 3.

TABLE 9.—RELATIVE SUSCEPTIBILITY OF ANNUAL FLOWERS, VINES, ETC. TO ROOT ROT[1]—*Continued.*

Susceptibility	Plant	Botanical name
Moderately susceptible	Portulaca	*Portulaca grandiflora* Hook.
	Scabiosa, sweet	*Scabiosa atropurpurea* L.
	Summer cypress	*Kochia scoparia* Schrod. var. *trichophylla* Bailey
	*Sunflower, common	*Helianthus annus* L.
	Sunflower, Maximilian	*Helianthus maximiliani* Schrad.
	Sweet sultan	*Centaurea moschata* L.
Slightly susceptible in summer (escape injury when grown as winter annuals)	Amaranth, tassel	*Amaranthus paniculatus* L.
	Balsam, garden	*Impatiens balsamina* L.
	Calendula	*Calendula officinalis* L.
	Gaillardia, common	*Gaillardia pulchella* Fouq.
	Gypsophila, annual	*Gypsophila elegans* Bieb.
	Joseph's coat	*Amaranthus tricolor* Hort.
	*Larkspur, annual	*Delphinium ajacis* L.
	Love-in-a-mist	*Nigella damascena* L.
	Love-lies-bleeding	*Amaranthus caudatus* L.
	Pink, Chinese	*Dianthus chinensis* L.
	Poppy, annual (Shirley)	*Papaver rhoeas* L.
	Poppy, opium	*Papaver somniferum* L.
	Prince's feather	*Amaranthus hypochondriacus* L.
	Stock, common	*Matthiola incana* R. Br.
	Sunflower, Mexican	*Tithonia rotundifolia* Blake (=*T. speciosa* Hook. ex Griseb.)
	*Sweet pea	*Lathyrus odoratus* L.
	Sweet William	*Dianthus barbatus* L.
	*Verbena, rose	*Verbena canadensis* (L.) Britton
	*Zinnia	*Zinnia elegans* Jacq.
Immune	Alyssum, sweet	*Alyssum maritimum* Lam.
	Amaranth, Globe	*Gomphrena globosa* L.
	*Balsam apple	*Momordica balsamina* L.
	Candytuft, sweet	*Iberis odorata* L.
	*Candytuft, white	*Iberis amara* L.
	*Cockscomb	*Celosia cristata* L.
	Coleus, common	*Coleus blumeri* Benth.
	*Gourd, dishrag	*Luffa acutangula* Roxb.
	*Gourd, white-flowered	*Lagenaria leucantha* Rusby
	Mignonette	*Reseda odorata* L.
	Mock cucumber	*Echinocystis lobata* Torr. & Gray
	*Nasturtium, bush	*Tropaeolum minus* L.
	*Nasturtium, climbing	*Tropaeolum majus* L.
	*Pansy	*Viola tricolor* L.
	*Petunia	*Petunia hybridum* Vilm.
	Phlox, Drummond's	*Phlox drummondi* Hook.
	*Snapdragon	*Antirrhinum majus* L.
	Strawflower	*Helichrysum bracteatum* Ands.
	*Verbena, garden	*Verbena hybrida* Voss.
	*Wandering Jew	*Tradescantia fluminensis* Vell.
	Watercress	*Roripa nasturtium* (L.) Rusby

TABLE 10.—RELATIVE SUSCEPTIBILITY OF WEEDS OF CULTIVATED LANDS TO ROOT ROT.[1]

Susceptibility	Plant	Botanical name
Moderately susceptible	Amaranth, prostrate	*Amaranthus blitoides* S. Wats.
	‡Bindweed	*Convolvulus repens* L.
	Buffalo bur	*Solanum rostratum* Dunal
	Bur clover	*Medicago arabica* All.
	Canaigre	*Rumex hymenosepalus* Torr.
	*Cocklebur	*Xanthium italicum* Moretti
	*Croton, Texas	*Croton texensis* (Kl.) Muell. Arg.
	Dock	*Rumex crispus* L.
	Ground cherry, purple	*Quincula lobata* (Torr.) Raf.
	Ground cherry, soft	*Physalis mollis* Nutt.
	*Horse nettle, white (blue weed)	*Solanum eleagnifolium* Cav.
	Horseweed	*Leptilon canadense* (L.) Britton
	Jimson weed	*Datura stramonium* L.
	Lamb's-quarters	*Chenopodium album* L.
	Lettuce, prickly	*Lactuca scariola* L.
	‡Mallow, common	*Malva rotundifolia* L.
	Medic, black	*Medicago lupulina* L.
	Milkweed, broad-leafed	*Asclepias latifolia* (Torr.) Raf.
	*Potato, hog	*Hoffmanseggia densiflora* Benth.
	Ragweed, common	*Ambrosia artemisifolia* L.
	Ragweed, perennial	*Ambrosia psilostachya* DC.
	‡Sow thistle, spiny	*Sonchus asper* (L.) All.
	‡Sunflower, common	*Helianthus annus* L.
	Thistle, Russian	*Salsola pestifer* A. Nels.
Slightly susceptible or immune	Calthrop, hairy	*Kallstroemia hirsutissima* Vail
	La golondrina	*Euphorbia albomarginata* T. & G.
	‡Puncture vine[2]	*Tribulus terrestris* L.
	Saltbush, annual	*Atriplex wrightii*
	Sheep sorrel	*Rumex acetosella* L.
	Boerhaavia	*Boerhaavia* sp.
	Tumbleweed	*Amaranthus albus* L.
Immune	†Filaree	*Erodium cicutareum* L'Her.
	Filaree, Texas	*Erodium texanum* Gray
	Peppergrass	*Lepidium apetalum* Willd.
	All grasses and sedges	
	All other plants with parallel-veined leaves (monocotyledons)	

[1] For explanation of symbols, see footnote under Table 3.

[2] A very common weed in root-rot spots; never found infected.

TABLE 11.—SUSCEPTIBILITY OF VARIOUS WOODY PLANTS GROWN AT THE SOUTHWEST ARBORETUM, SUPERIOR, ARIZONA.[1]

Botanical name	Remarks
The following plants have died of Phymatotrichum root rot:	
Acacia aneura F. Muell.	
Acacia longifolia Willd.	Sydney golden wattle
Acacia retinodes Schlecht. (= *A. neriifolia* A. Cunn. ex Benth.)	
Cercis griffithii Boiss.	
Dendromicon rigida Benth.	Bush poppy
Dodonea viscosa L.	Native to Arizona
Eucalyptus melliodora A. Cunn. ex Schau.	
Eucalyptus redunca Schau.	
Eucalyptus viminalis Labill.	
Lagunaria patersonii Don.	
Parosela greggii A. A. Heller (= *Dalea greggii* A. Gray)	
Pistacia terebinthus L.	1-year-old tree died
Rhus lancea L.	
Schinus dependens Orteg.	
Schinus lentiscifolius March.	
The following plants show apparent resistance:	
Celtis australis L.	Probably resistant
Erethea elliptica	
Eucalyptus canaliculata Maiden	Show distress
Eucalyptus rostrata Schlecht.	Show distress
Eucalyptus rudis Endl.	Show distress
Koelreutheria paniculata Laxm.	Infected but recovered
Padus virens Woot. & Standl.	Native to Arizona
Sageretia theezans Brongn. B.P.I. No. 22987	In infected area—no sign of injury
Simmondsia californica Nutt.	In infected area—no sign of injury
Ulmus anorosowi	Infected but made new growth

[1] These data are from the records of Director Fred Gibson and field observations by the writer. This table includes only plants not listed in tables 3 to 10. Many of the species listed here are foreign importations and not at present available commercially.

TABLE 12.—RELATIVE SUSCEPTIBILITY OF NONCULTIVATED SOUTHWESTERN PLANTS TO NATURAL INFECTION BY THE ROOT-ROT FUNGUS.

Authority	Plant	Botanical name
King et al.	"Plant showing evidence of definite injury":	
	Spurge	*Chamaesyce albomarginata*
	Jimmy weed	*Aplopappus heterophyllus*
	Sphaeralcea	*Sphaeralcea ambigua*
King et al.	"No lesions or rotted tissues. Typical strands present":	
	Mesquite	*Prosopis velutina*
	Condalia	*Condalia lycioides canescens*
	Tree cholla, slender	*Opuntia arbuscula*

TABLE 12.—RELATIVE SUSCEPTIBILITY OF NONCULTIVATED SOUTHWESTERN PLANTS TO NATURAL INFECTION BY THE ROOT-ROT FUNGUS—*Continued.*

Authority	Plant	Botanical name
King ('34)	"Strands on dead or dying plants":	
	Mexican poppy	*Argenome* sp.
King ('34)	"Root-rot fungus on roots or stumps":	
	Mesquite, velvet	*Prosopis velutina*
	Squawberry	*Lycium* sp.
King ('34)	"Root-rot carriers":	
	Franseria	*Franseria confertifolia*
	Snakeweed	*Gutierrezia lucida*
	Arizona sycamore	*Platanus wrightii*
	Bagote	*Parkinsonia aculeata*
	Spiny aster	*Aster spinosa*
	Blue paloverde	*Cercidium torreyanum*
Rogers ('36)	"Plants most readily observed as infected or dying with root-rot":	
	Wild sunflower	*Helianthus annus*
	Perennial sunflower	*Helianthus maximiliani*
	Green milkweed	*Asclepiodora viridus*
	Tall goldenrod	*Solidago altissima*
	Perennial ragweed	*Ambrosia psilostachya*
	White-wreath aster	*Aster multiflorus*
	Spurge nettle	*Tragia* sp.

SYMPTOMS

An infallible sign of the presence of the root-rot fungus is the appearance of the spore mats (Plate VIII) in moist soil. Spore mats vary from 2 to 12 inches in diameter and are snowy white with the texture of absorbent cotton when first formed, but within two days become tan in color and powdery in texture although the growing margin remains white. These spore mats usually appear only during the period of summer rains (July to September, inclusive) and appear within a few days following rain or an irrigation. While they are most abundant and luxuriant in shady spots, this is apparently due to more favorable moisture conditions in the shade, as they are also formed in direct sunshine. The writer has found them much more abundant in alfalfa than in cotton, comparing adjoining fields. They are much more prevalent some years than others—they were more prevalent in the vicinity of Tucson in the summer of 1936 than for at least the five previous years. In alfalfa they formed practically a continuous ring around the advancing margin of each root-rot spot, surrounding the base of slightly or not visibly affected plants. Spore mats and their structure and significance are discussed in more detail in the section on the root-rot fungus. (See pages 341-42.)

While the sudden death of plants coupled with drying of foliage and decay of roots, with or without the presence of spore mats is

Plate VIII.—Spore mats of root-rot fungus in alfalfa field. The outer, younger zone is pure white and the inner zone after a few days becomes filled with a powdery mass of buff spores. x⅓

usually sufficient to diagnose root rot on any of its many host plants, the following reactions of certain host plants are of great value in the early identification of the disease, enabling control measures to be applied promptly and with better chance of success.

The fibrous and fleshy roots of sweet potato, and the taproots of cotton, okra, and some other plants show numerous small cushionlike fungus growths about the size of a pinhead, light colored at first but becoming darker and wartlike (plates XII and XVI). These bodies, like the fungus strands, are characteristic of the root-rot fungus and aid in its identification.

ON COTTON

The symptoms and progress of root rot in cotton is fairly typical of its behavior on other host plants. The first symptom visible in the field is a slight yellowing or bronzing of the leaves noticeable to the persons familiar with the disease from one to several days before any further symptoms develop. Soon after the color change a slight wilting of the upper leaves is noticeable, followed by a wilting of the lower leaves in midafternoon. Wilted plants may temporarily recover following a cool night, rain, or irrigation, but permanent wilting follows within a few days. Within twenty-four hours after wilting the leaves become brown and dry but

Plate IX.—Infected cotton root magnified 4 diameters to show root-rot strands on surface of root. x4.

remain attached to the plant. The roots of plants even in the first stage of wilting will be found extensively decayed (Plate IX), and usually the dead roots show a network of fungus strands (Plate XXIII) on their surface. These strands are most abundant in late summer when the disease is most active, in soils well supplied with moisture, and on roots recently attacked by the fungus. The dead cotton roots decay rapidly and the root-rot strands may disappear from the surface of the roots within a few weeks.

It has long been known that leaves of plants showing bronzing or wilting felt warmer than the leaves of normal plants. This difference has been measured and the temperature of affected leaves found to be 2 to 5 degrees F. higher than that of normal leaves, due to lack of water for normal cooling by transpiration in the leaves of affected plants.

Cotton plants are not killed in the field when under one month in age, due probably to the fact that root rot does not become evident in Arizona cotton fields before the middle of June rather than any inherent resistance of the young cotton plants. The disease spreads from the first centers of infection, killing plants in roughly circular patches 20 to 30 feet in diameter. Where many centers of infection occur close together the circles overlap and the circular pattern is lost. Late in the season (September to November) affected plants which may or may not have lost their

leaves may show partial recovery by putting out new growth from the central stalk, but often the recovery is temporary.

The patches of dead cotton plants with the dried leaves clinging to the browned and blackened stems are not easily confused with those arising from other causes except perhaps an occasional spot where plants have been killed by lightning. The lightning spot, however, appears suddenly and does not grow in size, the stems are often split and shredded and the roots of plants on the margin of the spot are not killed. Waxahachie wilt, caused by another root-invading fungus, occurs in Arizona but does not cause immediate and extensive decay of the roots.

ON ALFALFA

The field symptoms in alfalfa are similar to those in cotton. A typical root-rot spot (Plate I) is roughly circular in outline with only a few scattered surviving plants which are stunted. At the

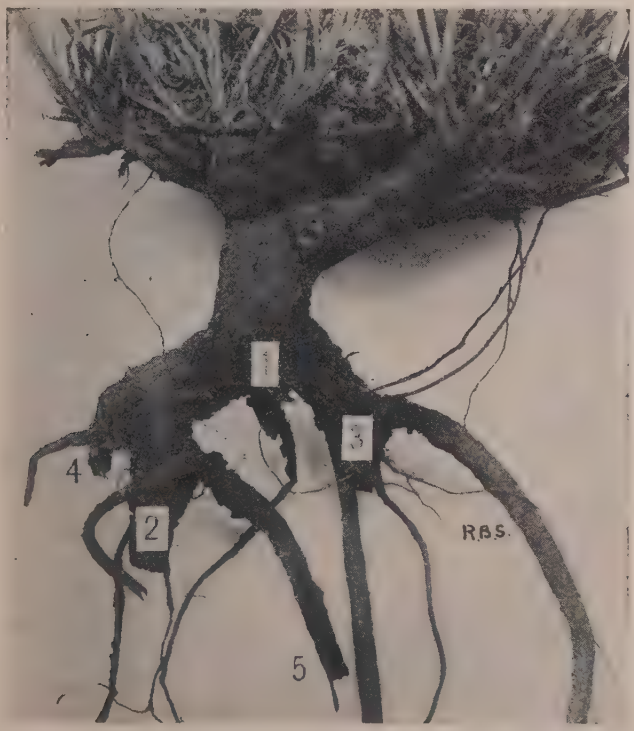

Plate X.—Crown and root system of alfalfa plant which has survived successive attacks of the root-rot fungus. The numbers *1* to *5* indicate the stubs of roots in approximately the order in which they were killed. The plant was apparently healthy when dug.

margin of this area is a zone of dead and dying plants, and beyond these are apparently healthy plants. If the latter are dug up, however, it will be found that the infection has already reached the taproots of plants from 1 to 3 feet beyond the last wilted plant.

The newly infected plants make an apparent recovery when the field is cut and irrigated, for the injured roots are then able to supply food and moisture to the reduced tops. After the new growth has reached a height of 6 inches the normal rate of dying of plants on the margins of the root-rot spots is resumed.

Alfalfa plants which have apparently survived the attack of root rot and have been carefully dug out, in all cases thus far observed, have a taproot which has been killed (120, 138). Such plants depend entirely upon one or more lateral roots in normal position or upon a lateral which has turned downward and become, in effect, a taproot. Infected plants have been found which have lost this "taproot" through repeated attacks of the root-rot fungus no less than five times (Plate X).

ON TREES

On pepper trees

While pepper trees which are very susceptible to root rot sometimes die practically overnight with the dead leaves clinging to the twigs, they usually first show infection by a shedding of the leaflets, sometimes to the extent that the tree is practically defoliated. A sudden shower of leaflets suggests an immediate examination of the root system for root rot (Plate IV).

On pecan and Arizona ash

These partially resistant species occasionally die suddenly, but usually show distress for one or more seasons before dying. The top growth becomes scant, the foliage small and somewhat pale and yellowish and the top of the tree thin (Plate XXVII *B*). Since other unfavorable conditions such as insufficient irrigation or poor soil might cause such symptoms, an examination of the root system of suspected trees should be made.

On mulberry and bottle trees

These trees likewise sometimes die suddenly but often show yellow foliage and reduced growth for some months before the attack proves fatal (Plate V).

On Japanese euonymous

The usual deep green, glossy foliage of this popular shrub loses its luster and becomes dull and pale green under the attack of the root-rot fungus. Being quite susceptible the affected plants soon die, and the leaves dry and bleach without being shed.

Plate XI.—Apricot tree which died "overnight" from root rot. When photographed the foliage was still green but dry and crisp; a few days later it had turned to a light brown.

On fruit and shade trees

Fruit and shade trees in most cases die suddenly within a few days usually without any preliminary symptoms noticeable to the owner. The slight bronzing or yellowing and wilting and "feverishness" of foliage is usually discernible to the trained observer. Occasionally a tree will die so rapidly that the foliage retains its green color although dry and brittle (Plate XI), but the color is soon lost by weathering.

CAUSAL ORGANISM

Back in the eighties when "dead spots" or dying of cotton began to attract attention, Texas cotton growers had many theories as to its cause. Much prominence was given to the idea that certain chemical or physical conditions of the soil, such as alkali, excess of lime, and lack of drainage, caused the roots to decay. In 1888 Pammel (91) after a preliminary survey announced that the disease was caused by a fungus, a species of Ozonium which was identified by Dr. W. G. Farlow as *Ozonium auricomum* Link, a species very prevalent in Germany. The identity of the Texas and German fungi was questioned (1, 9, 109), but not until Shear was able to compare the Texas Ozonium with Link's type in Berlin where they proved to be distinct, resembling each other only in color. Shear (109) described the Texas fungus as a new species, giving it the name *Ozonium omnivorum* Shear.

Plate XII.—Cotton root enlarged 5 diameters to show filaments of root-rot fungus on surface and white, cushionlike growths which are characteristic of the fungus on certain host plants.

When the spore mats first associated with the fungus by Thornber (150) were described by Duggar (16) in 1916 the name of the spore form took precedence and the botanical name of the fungus became *Phymatotrichum omnivorum* (Shear) Duggar.[5]

Recently Presley and Thom (96) examined spore mats covered during their development to protect them from sun, wind, and insects and found the mature spore mass covered by a loose felt or membrane of hyphae and suggest that the mat is not a Hyphomycete fruiting body but resembles a Gasteromycete (puffball) or some obscure accessory structure of an Ascomycete.

This fungus is invariably found in or on the roots of plants dying or recently killed by root rot. It has been repeatedly isolated in pure culture from naturally infected plants and the disease transferred to normal plants by inoculating them with the pure

[5] Duggar (15) reports finding the spores and suggested that the fungus might be the oidial stage of some Basidiomycete.

cultures. The fungus has then been reisolated in pure culture from the inoculated plants, completing the chain of evidence that this fungus is the cause of root rot.

VEGETATIVE (OZONIUM) STAGE

The vegetative filaments (hyphae) of most fungi advance from the original center of growth by simple, often much branched filaments producing a visible growth much finer but similar in texture to a weft of cotton fibers. A few fungi, including the root-rot fungus, produce an elaborate system of strands composed of many closely interwoven individual filaments. In the case of the oak-root fungus (*Armillaria mellea*) the strands (rhizomorphs) are as large as the lead of a pencil, black and smooth on the outside, white inside. In the root-rot fungus the strands are smaller, appearing like pieces of fuzzy, tan to brownish thread (Plate XII). The strands branch more or less and between the strands there is a delicate weft of single filaments (Plate XIII). The strands push rather rapidly through the soil until they find healthy roots of a susceptible plant which they envelop and penetrate, or failing this, grow until their food supply is ex-

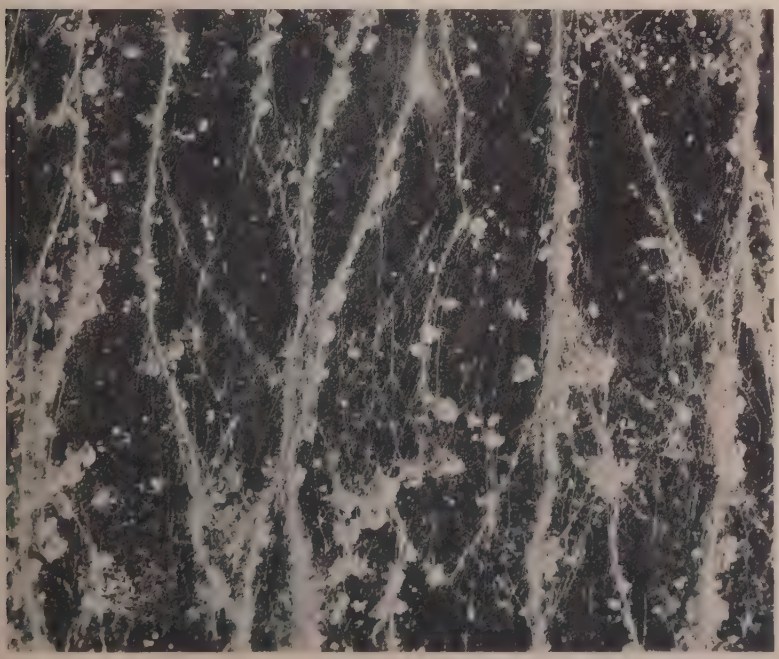

Plate XIII.—Enlarged photograph of root-rot strands and the single fungus filaments which permeate the soil between the strands. x5.

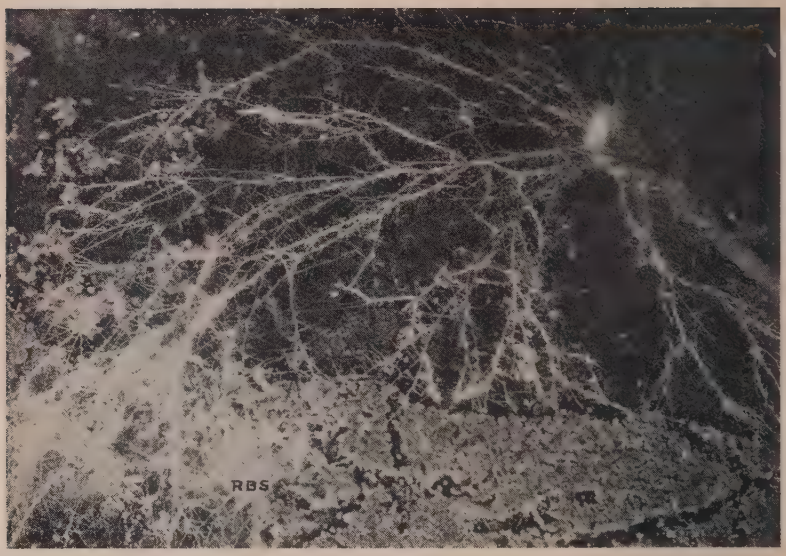

Plate XIV.—Strands of the root-rot fungus arising from end of a dead cotton root and spreading through surrounding soil. The strands are light colored at first. x2.

hausted. They appear to function like the familiar underground rootstalks of Johnson grass or bindweed (Plate XIV).

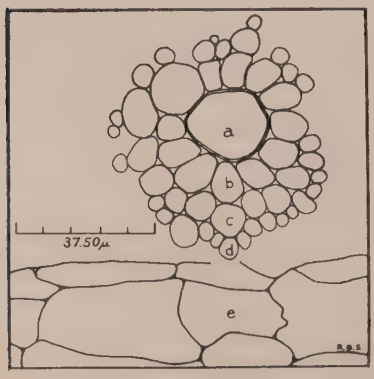

Figure 3.—Cross section of strand on surface of alfalfa root. The strand is composed of a large-celled central hypha (*a*), surrounded by several layers of small hyphae (*b*, *c*, and *d*). The cortex of the alfalfa root is shown at *e*. Camera lucida drawing from stained microtome section.

Structure of strands

When the slender, fuzzy strands are placed under the low power of the microscope, they show a solid central core with an abundance of slender, tapering side branches which produce the fuzzy appearance to the naked eye (Plate XV). These slender, tapering side growths branch once or twice in opposite directions, the branches standing stiffly at right angles to the main axis. These cruciately-branched acicular hyphae (Fig. 4 *D*) are so far as we know unique in the fungus world and are very useful in identifying the root-rot fungus.

The individual fungus filaments (hyphae) are of two diameters, large and small (Fig. 4 *A*). The core of the strands is com-

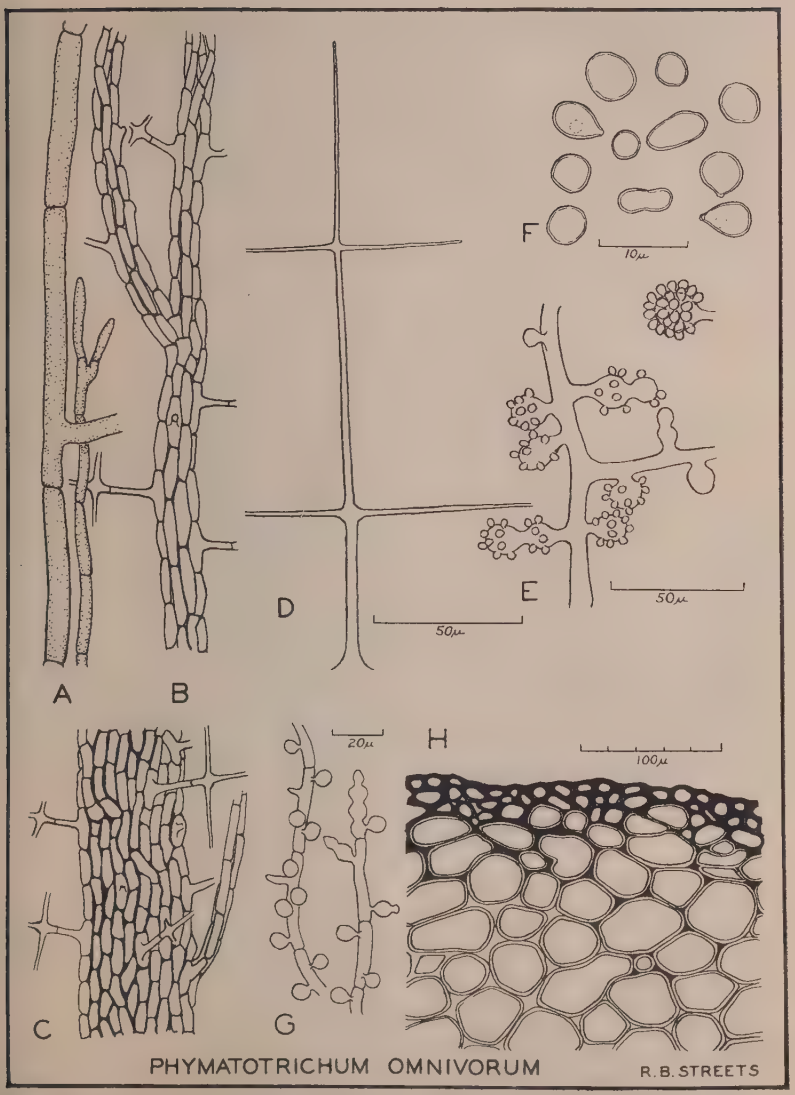

Figure 4.—Morphology of *Phymatotrichum omnivorum*: *A*, large-celled and ordinary mycelium; *B*, young strand; *C*, mature strand; *D*, acicular hypha; *E*, conidia and conidiophores from spore mat; *F*, conidia; *G*, conidia borne laterally on vegetative hyphae; *H*, cross section of sclerotial tissues.

posed of a very large hypha surrounded by several layers of interwoven smaller hyphae. The large hypae are likewise found in the

Plate XV.—Low-power photomicrograph showing buff-colored strands from the surface of an infected cotton root.

mycelial weft on the surface of infected roots, but they appear to be short-lived. Both individual filaments and strands are light colored when young but soon turn to buff or brownish. The development of strands and acicular hyphae is greatest in soil and least on artificial media.

Smooth strands and sclerotial strands

Old strands and those formed during the cooler months are usually small and dark brown in color with few or no acicular hyphae. The ordinary fuzzy strands are often short-lived, and pure cultures can very seldom be obtained from detached fragments of such strands (57, 81). A special modification of strands, however, to form resting bodies (sclerotial strands) which no doubt enable the fungus to withstand unfavorable conditions has been observed by Dana (10) and Ratliffe (98). McNamara et al.

(70) obtained viable strands from Texas soils after two years in oats and five years in clean fallow and believe that some of the viable strands were three years or more of age.

SPORE-MAT (PHYMATOTRICHUM) STAGE

Only during the period of summer rains (July to October) does the root-rot fungus appear above ground in the form of spore mats, which constitute the asexual or conidial stage of the organism. Under conditions favoring their development (moist soil and warmth) their rapidity of growth is mushroomlike, for they spring up overnight and complete their formation of spores within three or four days. While varying widely in size and thickness (the writer has measured mats from 1 to 16 inches in diameter and from about ⅛ to ¾ inch in thickness), the usual size is from 4 to 8 inches in diameter and about ¼ inch thick.

The spore mat develops from a "root system" of Ozonium strands appearing first as a fluffy white growth resembling absorbent cotton in texture and color. The second day the older, central portion has changed to a creamy white or pale buff, and usually the third day the texture has changed from cottony to powdery and the color to a buff or fawn, called by Ridgway (104) cinnamon buff. If the soil remains moist the margins of the mats may continue to grow for some time. The mature spore mats are composed almost entirely of the extremely minute spores of the fungus which are usually soon weathered away leaving the ground almost bare with just a trace of the buff color remaining to mark the location of the mats. If the freshly matured mats are wet by rain or irrigation water, a thin, darker brown crust is formed on the surface of the mat. Successive crops of mats may occur in the same location. Mats may occur on level ground but are often more numerous in depressions such as ditch banks, gopher holes, furrows, trenches, tree holes, or other places where the surface soil remains moist for several days.

Microscopic examination reveals that the spore mat in the early, white stage is composed of large-celled, much-branched hyphae resembling those in the vegetative strands. As these hyphae mature they develop swollen tips and side branches on which the tiny spores are borne (Fig. 4 *E*). From ten to thirty-six or more spores are borne on each of the swollen tips (conidiophores) and spores are also borne on the surface of unspecialized hyphae (Fig. 4 *G*). The spores are smooth, globose, with an average diameter of 4.8 to 5.5μ or ovate with an average measurement of 5 to 6 by 6 to 8μ.

Germination of spores

The function of these spores and their value to the fungus, if any, is at present unknown. Many investigators (16, 93, 139, 147e, 148) have attempted to germinate the spores, using material of all ages under widely varied conditions, in or on a great variety of liquid and solid culture media but without success. Occasion-

ally a very few of the spores will swell somewhat or put out a feeble germ tube, but no mycelium capable of normal growth has yet been reported. Between 1925 and 1929 this laboratory tried to germinate these spores in many different nutrient solutions and chemicals without success (114, 116). As the spores are difficult to wet, various treatments were tried to remove the water-resisting substance from the surface of the spores, but they still refused to germinate.

Both field evidence and the failure of the writer and others (93, 139, 147d) to produce root rot by planting susceptible plants in soil inoculated with spores indicate that root-rot spores have very slight if any significance in the spread of the disease. They remain, however, a convenient and valuable indicator of the presence of the aggressive root parasite which normally stays below ground.

POSSIBILITY OF OTHER SPORE STAGES

Since fungi commonly have more than a single spore stage, there has been much interest in the possibility of a second sexual or perfect stage of the root-rot fungus which might explain some phases of its erratic behavior. In 1925 Shear (112) believed he had traced a connection between root-rot strands and a small fungus producing orange-yellow, somewhat gelatinous spines about ⅛ inch long in the center of a cottony growth on the stems of Osage orange suffering from root rot. He named the fungus *Hydnum omnivorum*. This fungus or similar species are not uncommon in cotton fields, but no other investigators have been able to verify the connection between the Hydnum and the root-rot strands, so it is very probable that the two fungi are distinct.

PSEUDOSCLEROTIA

In 1896 Atkinson (2) who was one of the first to obtain the root-rot fungus in pure culture reported the presence of sclerotiumlike bodies in his cultures. He described them as "from very small to 3 millimeters (⅛ inch) in diameter, whitish and wooly, finally becoming of the same color as the filaments of the fungus." In 1923 Taubenhaus and Killough (148) also reported that these bodies, which they termed "pseudosclerotia" occurred singly or in large masses in cultures on various media and on host plants in natural surroundings. The writer is inclined to agree with King and Loomis (57) that there is some doubt whether the "wartlike" bodies described by several investigators (2, 41, 92, 148) as commonly occurring on the infected roots of certain plants are analagous to the pseudosclerotia formed in culture or in loose soil. The bodies we have commonly observed on the roots of sweet potato (Plate XVI), cotton, and some other plants are composed of small tufts of hyphae.

Pseudosclerotia develop readily in pure cultures on the roots of such susceptible plants as cotton (Plate XVII), sweet potato,

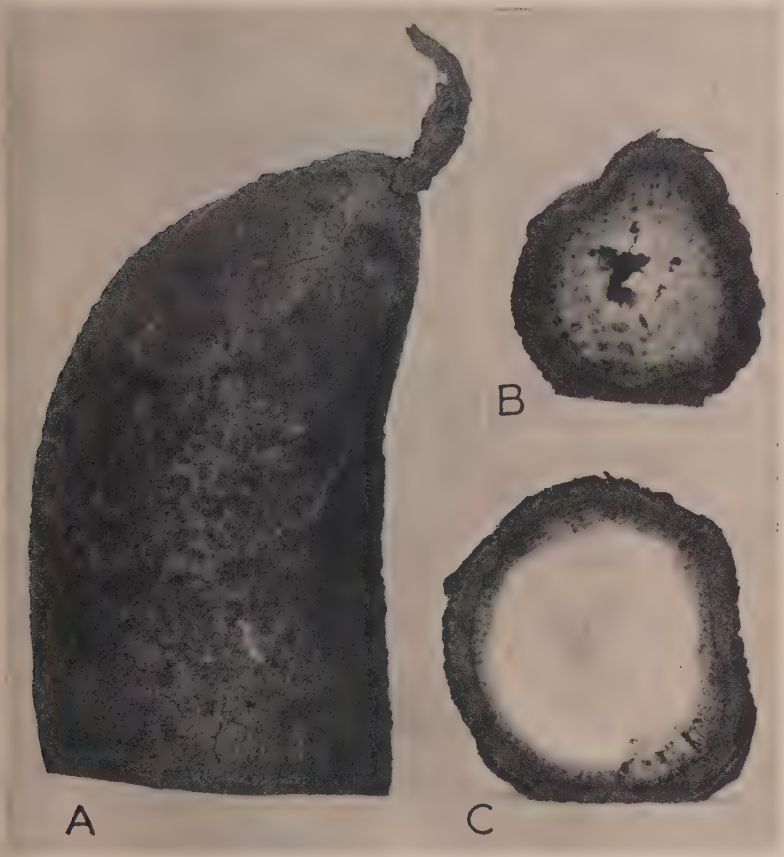

Plate XVI.—Sweet potato invaded by root-rot fungus. The small, wart-like spots are a type of fungus growth found on sweet potato, cotton, and some other host plants. x1.

alfalfa, and peach, and only very slowly on the sterilized roots of monocotyledonous plants such as date palm and Johnson grass (58). These structures develop best on a moist medium and are often aerial in character or formed in cavities in the soil or medium and have not been observed in compact soil.

Small fresh pseudosclerotia or fragments of large ones give a convenient source of inoculum for propagating cultures as these pieces seldom fail to grow, producing new hyphae in three to four days at 77 degrees F. (57). While they may survive several months under optimum conditions, they are not resistant to drying.

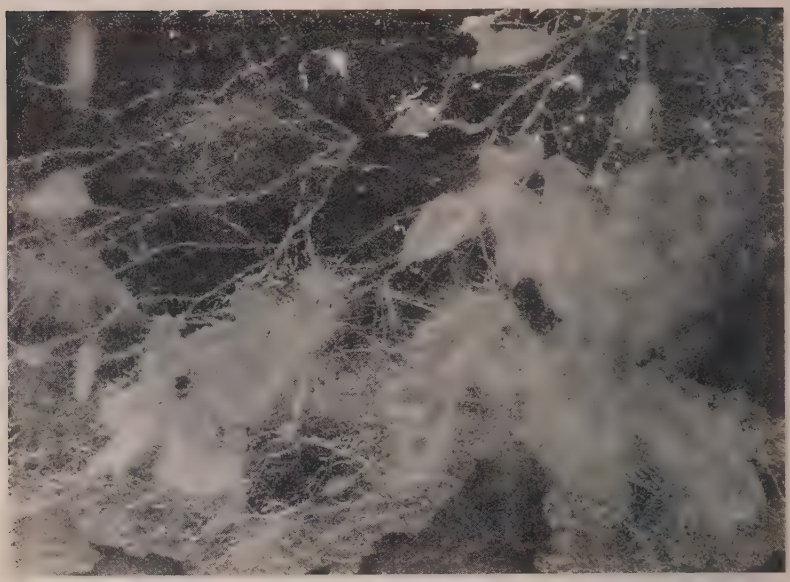

Plate XVII.—Root-rot fungus (*Phymatotrichum omnivorum*) in culture showing strands and young pseudosclerotia. x8.

SCLEROTIAL STAGE

Much of the mystery concerning the ability of the root-rot fungus to persist in an erratic and unpredictable fashion in fields which had been in clean fallow or planted to immune crops for periods of one to five years was cleared up by the discovery that the fungus produced tiny vegetative resting bodies called sclerotia similar in function to the potato tuber in that after lying dormant they can resume growth when conditions are again favorable.

The discovery of a true sclerotial stage was reported by King and Loomis (57) who found sclerotia in laboratory cultures in September, 1928. The relationship of these bodies was confirmed by Neal (76) who first reported the discovery of sclerotia under natural conditions in the soil and by Taubenhaus and Ezekiel (136) who also found sclerotia under field conditions in Texas.

Description of sclerotia

The mature sclerotia are small, mustard-seed-like bodies, variable in color from a light brown to a very dark brown, and color is no accurate measure of their age or viability. Sclerotia are also variable in shape, usually roughly spherical, but sometimes ovate or elongate or irregular, and produced singly or in chains or clusters (Plate XVIII).

Morphology of sclerotia

The structure and formation of sclerotia have been carefully studied by King and Loomis (57) and Neal, Wester, and Gunn (88). The sclerotia are formed by division and growth of the large-celled hyphae and adjacent cells comprising the core of the strands. The large-celled hyphae are still visible in sections of young sclerotia, but mature sclerotia usually show only a surface layer several cells deep of dark, thick-walled epidermal cells and a central portion of closely packed, thin-walled cells of irregular shape. The surface of young sclerotia, especially those produced in culture, is more or less covered with the acicular hyphae found on the strands, but these are not so apparent on older sclerotia.

Germination of sclerotia

The sclerotia germinate promptly at favorable temperatures making a growth of white hyphae about 8 millimeters (⅓ inch) in diameter in twenty-four hours at 75 degrees F. When surface sterilized by thirty to sixty seconds' immersion in 1:1,000 mercuric chloride, followed by rinsing in sterile water, they offer the most reliable and satisfactory source of pure cultures of the root-rot fungus. King and Hope (50) found that any part of a viable sclerotium was capable of growth. Specimens from which the outer coat was removed, fragments of the outer coat, and thin cross sections all produced mycelium. Taubenhaus and Ezekiel (136) demonstrated that the same sclerotia would germinate as many as five times after the previous growth has been removed.

Longevity and viability of sclerotia

Sclerotia under natural conditions usually remain viable over considerable periods of time. This is especially true of the sclerotia in the deeper layers of soil where moisture and temperature conditions remain relatively constant. King and Hope (50) secured prompt and vigorous germination of jar cultures containing sand and cotton roots kept in the laboratory over two and one half years, surpassing their previous record of successful inoculation with sclerotia eleven months old (59). Taubenhaus and Ezekiel (143, 144) were able to germinate 12 per cent of a lot of sclerotia after five years' storage in the laboratory in moist soil (20 to 40 per cent on an air-dry basis), while sclerotia stored at 10, 50, and 60 per cent moisture and in water failed to germinate after twelve months.

Sclerotia have been frequently found under circumstances which make it clear that they have survived in soil for considerable periods. Sclerotia were found under wilted plants in primary centers of infection at Greenville and San Antonio following two-year grain rotations (76). Dana (10) made similar observations on cotton following eighteen months' fallow, and others (22, 112, 135, 148) have reported finding viable sclerotia in the field. McNamara and Hooton (64) found that most of the primary centers of infection in Texas blackland soils (Houston and Wilson clays)

yielded either sclerotia or infected decayed roots or both. They attach considerable significance to the abundance of sclerotia in primary centers following several years of nonsusceptible crops or fallow, whereas no sclerotia were found in plots planted continuously to cotton. They infer that sclerotia are connected primarily with the saprophytic phase of the fungus and serve as a resting stage. Neal, Wester, and Gunn (88) confirm these results, observing that the sclerotia found following rotation or fallow showed signs of age—dark color, a noticeably tough rind, and absence of acicular hyphae.

Recent experiments (49) indicate that the catalase activity of the macerated tissues of sclerotia as a rule declines with age, and that a great or abrupt reduction in this activity occurs only in sclerotia beginning to lose germination power. This may be comparable to the after-ripening process which takes place in certain seeds. This activity may serve as an indicator of age and as a test for varying degrees of vigor or death. Catalase activity rapidly declines when the sclerotia are dried.

While long-lived in soil, sclerotia succumb quickly to exposure to drying. King, Loomis, and Hope (59) report sclerotia of average size killed by: (1) seventy-five minutes' exposure to air; (2) hot water (115-116 degrees F.) in fifteen minutes; (3) 1:1,000 mercuric chloride solution in four to five minutes or a 1:2,000 solution in about thirty minutes; (4) 1 per cent commercial formalin solution in thirty minutes; and (5) the gas from a 1.5 per cent solution of formalin in twenty-one hours. They resist immersion in water, however, 81 per cent surviving ninety-two days and 20 per cent surviving 121 days in distilled water, and they are apparently not injured by widely fluctuating temperatures. Fifteen minutes in hot water at 115 degrees F. will kill individual sclerotia. When sclerotia and sections of infected cotton root ½ inch in diameter were placed in the center of quart jars filled with sand and the jars immersed in water, 109.5 degrees F. for two to four minutes, the sclerotia were killed, but a temperature of 124 degrees F. was required to kill the mycelium on and in the root tissues.

King and Eaton (48) made monthly tests for one year of viability on lots of sclerotia buried in soils maintained at different moisture contents. Viability was destroyed within three months in air-dried soil and soil with 5 per cent moisture and best preserved at moisture contents of 25 and 28 per cent (saturated). Some sclerotia germinated spontaneously in soils of 10, 25, and 28 per cent moisture, the hyphae penetrating the clay containers and forming mats of mycelium on the outside.

Development of sclerotia

The writer has followed the development of sclerotia from their first appearance to maturity using soil cultures in 2-quart Mason jars inoculated with root-rot-infected roots of cotton or alfalfa. In moist, well-aerated soil the fungus grows well at room temperatures spreading along the glass walls through which it can be

Plate XVIII.—Abundant sclerotia formed in soil culture. The soil was carefully washed away to secure a contrasting background. x2.

observed. Slight spindle-shaped swellings (Plate XIX *A*) were observed while the young mycelium still retained its white color The swellings were formed from 2 to 3 inches behind the advancing tips of the hyphae. The young sclerotia grew rapidly becoming full-sized, roughly spherical bodies from 1 to 3 millimeters in diameter in four to five days (Plate XIX *C*) and mature in ten to fourteen days (Plate XIX *D*). At this time both sclerotia and the strands bearing them turned dark, the sclerotia becoming

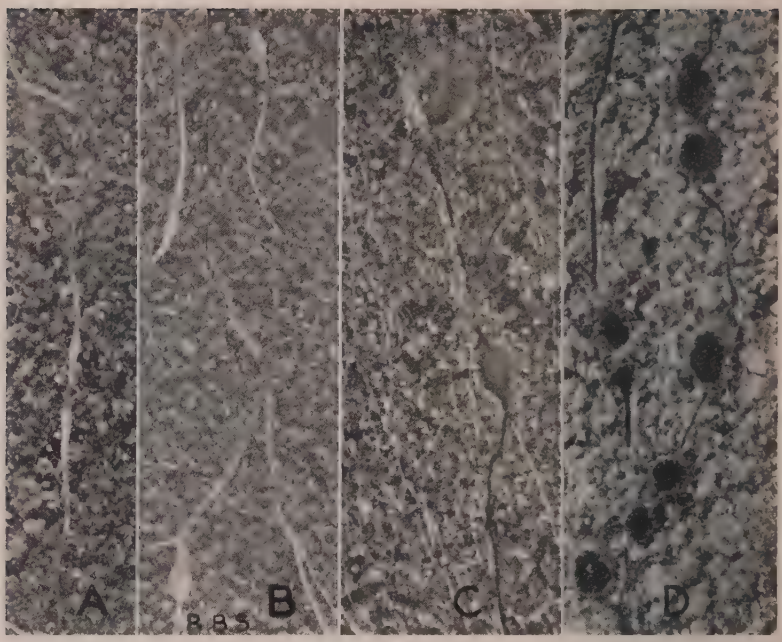

Plate XIX.—Stages in the formation of sclerotia: *A*, spindle-shaped swellings on young, light-colored strands; *B*, spindle-shaped swellings several days later; *C*, full-sized but immature sclerotia; *D*, mature, dark-colored sclerotia. x4.

dark brown. In a set of twenty-four soil cultures usually only one third produced sclerotia, and some of these only a few. Occasionally a culture was found which produced sclerotia very freely (Plate XVIII) so that they were strung like beads on the strands. The light-colored growing sclerotia are covered with the typical fuzzy growth of acicular hyphae which gradually disappears as they darken and mature. The interior tissues of the sclerotia remain white.

Occurrence of sclerotia

Production of sclerotia appears to be a response of the fungus to an abundant food supply according to King, Loomis, and Hope (59) who observed the daily growth of the fungus in glass tubes containing sand or soil and noted the formation of sclerotia after the fungus had passed sterilized cotton roots placed at intervals in the tube. They likewise observed that new sclerotia may be formed periodically by a budding process from old sclerotial clusters, or directly from old strands, five or six months after the first sclerotia appear.

The number of sclerotia found in root-rot-infected soil is exceedingly variable. King (60) reports 444 per cubic foot of soil taken from beneath dying shade trees, or 8,800 per ton of soil, with a viability of 98 per cent. King and Hope (50) compute a population of 100,000 sclerotia in a cylinder of soil 5 feet in diameter and 6 feet deep containing the root system of an eleven-year-old Chinese elm killed by root rot. Reports from Texas (88, 105, 136) appear to indicate that the occurrence of sclerotia is more constant and uniform in that state than in Arizona. A large per cent of the samples taken in the vicinity of Tucson have contained no sclerotia.

Vertical distribution of sclerotia in soil

Sclerotia have been found in soil at all depths up to 8 feet (60, 139) but are most abundant in the zone between 6 and 24 inches below the soil surface, the region where plant roots are most abundant. King and Hope (50) found sclerotia abundant in cotton at depths between 12 and 24 inches, most numerous between 16 and 20 inches; abundant in alfalfa between 6 and 30 inches, most numerous between 12 and 18 inches; and abundant under Chinese elm between 6 and 48 inches. Under Arizona conditions sclerotia seem to be formed most abundantly during the early fall months. We found that they are not uniformly distributed in the soil but seem to occur in pockets. A soil sample of 25 to 50 pounds might yield abundant sclerotia while other samples taken under identical conditions only 2 to 10 feet away produced very few or no sclerotia. Series of samples taken at monthly intervals during the fall and winter of 1934-35 at Tucson gave one location in an alfalfa field where sclerotia were abundant in every sample taken, while a dozen other locations in infected cotton, alfalfa, and fruit trees produced relatively few or no sclerotia (Table 13).

Method of separating sclerotia from soil

In separating sclerotia from soil, the method suggested by King (57) of washing the soil sample through screens with water to remove the finer particles was followed. A 10-mesh and 20-mesh screen were used, and the residue left on the screen, consisting of rock fragments, organic debris and sclerotia, was brought to the laboratory for examination. A method of separation of the sclerotia which greatly speeded the work was developed. The sclerotia were found to sink in water but would float in solutions of considerably higher specific gravity. The heavier impurities were quickly separated by immersing the sample in a saturated solution of photographers' hypo (sodium thiosulphate). The floating fraction was caught on a sieve, rinsed, and placed in a porcelain evaporating dish and the organic debris washed away with a carefully controlled jet of water. The method is described in more detail in the Annual Report of 1934-35 (123). A very similar method was developed by Rogers (105), but he used a sugar solution instead of a hypo solution, and developed a power-

TABLE 13.—SCLEROTIAL COUNTS OF 20-POUND SAMPLES OF SOIL TAKEN AT DEPTH OF 6 TO 18 INCHES IN ROOT-ROT-INFECTED AREAS ON THE NEW UNIVERSITY FARM, TUCSON.

Date of sampling	Place of sampling	Activity of root rot	No. sclerotia per sample										Total no. sclerotia
			1	2	3	4	5	6	7	8	9	10	
Aug, 20, 1934	Peach-apricot orchard	Infected trees	0	[b]	0	1	0	0	0	0	0	0	31
Aug, 20, 1934	Alfalfa field N. of orchard	Root-rot spots	0	[c]	1	[d]	0	0					111
Aug, 20, 1934	Alfalfa field	Root-rot spots	0	0	0	0							0
Aug. 29, 1934	Cotton field	No active root rot	0	0	0	0	0	0					0
Aug. 29, 1934	Cotton field	Near infected plants	0	0	0	0	0	0					0
Aug. 29, 1934	Alfalfa	No root rot	0	0	0	0							0
Aug. 29, 1934	Alfalfa	Infected area	1	0	0	0							1
Sept. 8, 1934	Alfalfa field K	Infected area	0	0	0	0	0	0					0
Sept. 8, 1934	Alfalfa field J	Infected area	0	0	0	0	0	0					0
June 4, 1935	Alfalfa N. of orchard	Infected area	0	0	0	0	0	0	0	0	0		0
June 4, 1935	Orchard	Infected area	0	0	0	0	0	0	0	0	0	0	0
June 4, 1935	Cotton N. end	Infected area	0	0	0	0	0	0	0	0	9	0	9
July 30, 1935	Alfalfa field A	Base of diseased plants	1	0	0	5	0	4	0				10
July 30, 1935	Alfalfa field B		0	5	4	0	0	1	0				10
July 30, 1935	Orchard	Under spore mats	0	21	1	8	1	6	2				39
July 30, 1935	Cotton		0	1	18	25	0	0	0				44
Apr. 27, 1936	Alfalfa	Infected area	0	0	0	0	[a]	0					.....
Apr. 27, 1936	Orchard	Infected area	[a]	0	[a]	0	0	[a]					.....
Apr. 27, 1936	Cotton	Infected area	[a]	[a]	[a]	[a]	[a]	[a]					.....
Aug. 24, 1936	Alfalfa, pecans	Under spore mats	0	3	0	0	0	0	0	0			3
Aug. 24, 1936	Orchard	Under spore mats	5	0	0	0	2	0					7
Aug. 24, 1936	Cotton	Near wilting plants	0	0	0	11	30	1					42

TABLE 13.—SCLEROTIAL COUNTS OF 20-POUND SAMPLES OF SOIL TAKEN AT DEPTH OF 6 TO 18 INCHES IN ROOT-ROT-INFECTED AREAS ON THE NEW UNIVERSITY FARM, TUCSON—*Continued.*

Date of sampling	Place of sampling	Activity of root rot	No. sclerotia per sample										Total no. sclerotia
			1	2	3	4	5	6	7	8	9	10	
Sept. 15, 1936	Alfalfa, pecans	Under dead plants	0	0	4	0	10	0					14
Sept. 15, 1936	Orchard	Under dead or dying trees	0	0	0	1	0	3					4
Sept. 15, 1936	Cotton	Near dead plants	25	15	2	10	1	6					59
Nov. 7, 1936	Alfalfa	Infected area	0	0	1	0	1	0					2
Nov. 7, 1936	Orchard	Infected area	0	0	3	0	0	0					3
Nov. 7, 1936	Cotton	Infected area	9	0	6	1	0	0					16

[a] Sclerotia present.
[b] Sclerotia abundant, about 30.
[c] Sclerotia very abundant, about 50.
[d] Sclerotia extremely abundant, over 60.

driven machine to wash samples of soil more quickly and easily. Rogers found that many small sclerotia passed through the 20-mesh screen so he substituted a 35-mesh screen.

Constancy of sclerotial formation in infected areas

We are badly in need of a simple and accurate method of determining the presence of root rot in tilled or virgin soil in the absence of susceptible host plants. If sclerotia were found to be consistently present in infected soils, an examination of soil samples would reveal the presence of the disease. Repeated samplings of known infected areas over a series of several years have convinced the writer that the occurrence and distribution of sclerotia in root-rot spots is too uneven and erratic to be of value in predicting the amount of infection present in a field. An experimental plot, with a known history of severe root rot every year for three years in alfalfa and seven years in cotton, yielded no sclerotia at all in some series of samples (Table 13). The only alternative seems to be to wait for warm, cloudy weather following summer rains and look for spore mats. In both cases positive evidence is of value, but negative findings are not conclusive—ordinary sampling might easily miss infected areas entirely or fail to include areas in which sclerotia were produced, or root rot may be present but not active.

NEW SPECIES RESEMBLING ROOT-ROT FUNGUS

An undescribed fungus resembling *Phymatotrichum omnivorum* was recently reported from northeastern Texas by Neal and Wester (84, 85). This new species develops strands and sclerotia but differs from the root-rot fungus in the following respects: the strands are of finer texture; sclerotia are formed rapidly on agar; the fungus is easily cultured and apparently saprophytic on buried cotton stalks and roots; the mycelium lacks the right-angled branches or acicular hyphae; the hyphae are white when young, becoming pale yellow to buff with age; and the sclerotia are white to pale yellow, variable in size and shape, averaging 1 millimeter in width by 5 millimeters in length, usually ellipsoid or spindle shaped or variously constricted. The fungus *Ozonium texanum* Neal and Wester is so far as known of no economic importance.

PHYSIOLOGY

METABOLISM

As might be expected in case of an organism capable of attacking such a wide range of host plants, the nutritional requirements of the root-rot fungus are not very exacting. Atkinson (1), who first isolated the fungus in 1892, grew it on sterilized sweet potato, cotton roots, apple roots, and manure. Later, Duggar (16), Taubenhaus and Killough (148), and King and Loomis (56, 57) cultured the fungus on a wide variety of sterilized plant tissues (roots,

stems, seeds, and fruits) and agars made from such tissues. In our own laboratory we have found sterilized roots of cotton, alfalfa, or other host plants most satisfactory for carrying the fungus in culture. Ponomareff (97) found that the organism grew much more luxuriantly in cultures of cortical tissues (bark) than on the woody tissues of the same plants.

The metabolism of the fungus has been recently studied extensively by Ezekiel and Taubenhaus and their associates (30, 33), Neal and his associates (83, 87), and Moore (75). Ezekiel, Taubenhaus, and Fudge (33) from a detailed study of the growth of the organism on synthetic media report that it utilizes a variety of carbohydrate materials—various sugars, starch, and mannitol. They found the growth rate in media containing various amounts of dextrose above the minimum for growth. No indications of staling products, substances produced by the fungus and toxic to it, were found. Small quantities of carrot juice added to synthetic media resulted in disproportionately large increases in growth of the fungus, suggesting that some accessory growth-promoting material might be involved. Sclerotia developed most abundantly in media most suited for rapid and abundant vegetative growth, such as their Formula 134[9] (33).

Nitrogen metabolism

Nitrogen was used equally well according to Ezekiel et al. (33) from organic sources and inorganic ammonium and nitrate salts with ammonium nitrate apparently the best source of nitrogen. Working with concentrations of nitrogenous compounds several times stronger Neal, Wester, and Gunn (86, 87) secured scant growth with ammonium nitrate or ammonium sulphate and abundant growth with calcium nitrate, sodium nitrate, and potassium nitrate, with solutions containing equal amounts of nitrogen—approximately 12.4 grams per liter. Ammonia was found to be even more toxic, ammonium hydroxide 500 ppm killing mycelium in twenty minutes, and a 1 per cent solution killing sclerotia in five minutes. Gas liberated from 28 per cent ammonia killed mycelium in thirty seconds, inhibited germination of sclerotia in from ten to twenty seconds, and growth of the fungus from infected cotton roots was prevented by one minute's exposure. Six per cent solutions applied to infected mature cotton plants in the field in most cases killed the fungus but not the plants although the cortical and cambial tissues were injured.

Neal and Collins (79) recently reported that while mycelium in agar blocks was killed after twenty-four hours in ammonia water containing 50 ppm of NH_3, and sclerotia did not survive a one-hour immersion in a 300 ppm solution, a much greater initial concentration (between 900 and 1,025 ppm of NH_3) was necessary to eliminate the root-rot fungus in the low-lime phase of Houston clay soil.

[9] Formula 134 in grams per liter: peptone 4.2, ammonium nitrate 1.2, corn starch (commercial) 40, sucrose (commercial) 40, magnesium sulphate 0.75, dipotassium acid phosphate (K_2HPO_4) 1.5, agar 20.

Leach and Davey (61) reported in 1935 that either anhydrous ammonia or ammonium sulphate dissolved in irrigation water in concentrations of approximately 300 ppm of ammonia (NH_3) significantly reduced the percentage of infection of *Sclerotium rolfsii* on sugar beets, and that the increase in yield was more than sufficient to cover the cost of treatment.

The writer has since 1932 (117-24) made extensive tests of the effectiveness of ammonium hydroxide and ammonium sulphate solutions largely under field conditions. These experiments, discussed more fully under the section of control measures (pages 380-84), show that concentrations greater than 1 per cent of the hydroxide or 5,000 ppm of the sulphate (equivalent to 1,000 ppm of nitrogen) are toxic to the roots of trees and shrubs as well as of cotton and alfalfa and likewise to the root-rot fungus.

It seems evident that at these high concentrations the immediate effect of ammonium salts is fungicidal or fungistatic rather than nutritional, and this fact offers one of the most promising lines of attack in controlling the disease.

MOISTURE RELATIONS

Soil moisture is clearly one of the principal factors controlling the prevalence and severity of root rot. The disease is favored by fairly moist soils but is affected unfavorably by either very dry or very wet soils, so that soil moisture is the primary limiting factor during the summer growing season when temperatures are favorable for root-rot development. Since all cultivated land in Arizona in the root-rot areas is under irrigation and the soil is kept within the moisture range most favorable to the growth of the crop plants, and incidentally the root-rot fungus, this factor causes much less fluctuation in intensity than in Texas where the crops in most districts are raised on natural rainfall.

Texas publications (137, 148) comment on the rarity of root rot on crops growing in creek and river bottom lands that are subject to periodic overflows. Successful inoculations of cotton plants and overwintering proved that the soils were not unfavorable (137). Although the fungus mycelium survived only a few days in flooded soil in the laboratory, in field experiments root rot was not controlled by flooding for as much as 120 days (137). King (48) has shown that the sclerotia will survive long periods of immersion in water which gives a possible explanation of the failure of flooding.

The writer attempted flooding experiments in the Yuma Valley in 1928 and again in 1929 (114) (page 373), and in each case the amount of disease was reduced but eradication was not secured.

TEMPERATURE RELATIONS

Summer temperatures are most favorable for the development of root rot (129). It is favored by relatively high soil temperatures, optimum development occurring around 75 degrees F. Soil temperatures favorable for the growth of cotton are likewise

favorable for the root-rot fungus. Plants affected late in the fall are often not killed at that time although decay of the root system occurs to some extent throughout the winter and spring months.

Below the surface foot the soil temperatures are fairly constant and favorable for the slow steady growth of the root-rot fungus. Progress of root rot in cotton roots between frost (November 10-20) and April 1, we have found to be between 2 and 4 feet.

SOIL REACTION

The root-rot fungus on artificial media shows maximum growth at *p*H 7.0 (neutral), and its growth is completely inhibited at an acidity of *p*H 4.1 and at an alkalinity of *p*H 8.9 (132), both extremes being beyond the limits for good agricultural land. In general, only low percentages of infection or overwintering are obtained in soils more acid than *p*H 5.0 (29, 146). In soils from *p*H 6.0 to 7.0, high percentages of infection are obtained following infection, but infection decreases in succeeding years (146). In alkaline soils of *p*H 8.0 to 8.5 the percentage of initial infections is high and remains high for years. Root rot, in fact, is characteristically a disease of definitely alkaline soils and reaches its maximum destructiveness in soils above *p*H 7.5. As our Arizona cultivated soils range between *p*H 7.5 and 8.5 (and some even reach 9.5) they fall within the range most favorable for root-rot development. In neutral and acid soils the spread of the disease is much slower and the resulting losses are not serious.

The above suggests the possibility of root-rot control by changing the soil reaction, but any considerable and permanent change of reaction in soils under field conditions offers great difficulties. In the first place an acre-foot of soil weighs approximately 4,000,000 pounds and would require many tons per acre of any chemical to appreciably affect its reaction. In addition the chemical itself might set up unfavorable soil conditions for plant growth, and the cost would often be greater than the value of the land treated. Sulphur has been the most promising of the chemicals used, but the difficulty of mixing it evenly in the soil below the surface 6 inches has been a serious handicap. In addition, our irrigation waters are definitely alkaline and tend to undo the treatment. Further discussion of changes in soil reaction and use of chemicals on limited areas will be found on pages 379 and 387.

SOIL TYPE

Root rot first attracted attention on the black, waxy soils of Texas and was formerly considered to be limited to that type of heavy clay soils, especially the Houston clay in which it is so destructive (139). It is now known to occur on every type of soil from blow sand to heavy adobe (47) and the preference for the heavier types of soil is apparently correlated with the higher moisture holding capacity of these soils. Gilbert (37), however, says that the fungus seems to grow best, and hence the disease is most severe, where the soil aeration is the poorest.

A recent study by Fraps (36) of Texas soils in relation to the severity of root rot shows that texture, fertility, and reaction are important but not the only factors determining the severity of root rot. He finds that the disease generally occurs and causes much damage in soils of high fertility, as indicated by their content of nitrogen, phosphoric acid, and potash. They are also high in basicity, contain considerable quantities of lime, and are alkaline in reaction and heavy in texture. Soils on which cotton root rot rarely occurs are generally low in fertility and basicity, are neutral to slightly acid (pH 6.5), and are light in texture. The chemical composition of local areas of soil containing active root rot may be almost identical with that of adjacent soils on which root rot is not present. Chemical composition is simply one of a number of factors influencing the occurrence and virulence of the disease.

In Arizona root rot is noticeably more prevalent in the finer textured soils along streams and river bottoms and in alluvial valleys than on the coarser soils of the mesas. Under irrigation, however, it thrives in the coarser soils when their moisture content is maintained by frequent applications of water. In fact, the superior aeration in the mesa soils favors the growth of the organism. This is demonstrated by the more luxuriant growth of the fungus in soil cultures in glass-sided containers in which the container is filled with moist soil compared with other containers in which the same soil is compacted by watering.

Southern Arizona soils are characteristically low in organic matter and this condition seems favorable to the root-rot fungus. The decay of organic matter does not appreciably affect the alkalinity of the soil (90), but much more important is the fact that soils rich in decaying organic matter have also a rich and active soil flora of saprophytic organisms. This condition has been shown by King (52) to be definitely unfavorable to the root-rot fungus and to a large extent explains the success of large applications of manure or organic matter in preventing and treating root-rot infections. Butler (8) has shown that a common soil fungus, *Trichoderma lignorum*, inhibits the growth of or kills the root-rot fungus. Taubenhaus and Ezekiel (147b) report similar results with *Diplodia* sp. and *Trichoderma* sp. (No doubt other organisms have the same effect.) King and Loomis (57) likewise note many cases of the inhibitory action of fungi and bacteria contaminating their cultures of *P. omnivorum*.

SAPROPHYTIC GROWTH

The inability of earlier investigators to isolate the root-rot fungus from roots two or more weeks after they had been killed by the fungus (139, 148) led them to conclude that the fungus does not live saprophytically on the dead roots but survives on partially decayed roots in which it is constantly advancing at a slow or rapid rate depending upon temperature and moisture. The fungus does not require living plant tissues for food, as shown

by its ready growth on sterilized plant tissues and synthetic media and could theoretically survive on decayed roots until its food supply was exhausted, lacking competition of the other organisms mentioned in the preceding paragraph.

Shear (109) in his original description of the fungus called it a facultative parasite, and a majority of investigators have held that the organism might exist in the soil under certain conditions either as a saprophyte or a parasite. Ratliffe (98) presents observations from three U.S. Department of Agriculture field stations—Sacaton, Arizona, San Antonio and Greenville, Texas—showing that the cotton root-rot organism may be carried in an infectious condition in the soil over a period of several years on the roots of completely dead host plants, including pecan, mesquite, *Lycium* spp., and cotton. This survival of the organism on more or less deeply buried roots offers one reason why clean fallow and rotation programs cannot be guaranteed to eradicate root rot.

VARIATIONS IN FUNGUS

The existence of clearly defined and stable different strains of the root-rot fungus has not been generally recognized. Ezekiel and Taubenhaus (25) were able to select strains of dissimilar characteristics by using sclerotia or mycelium as inoculum, but

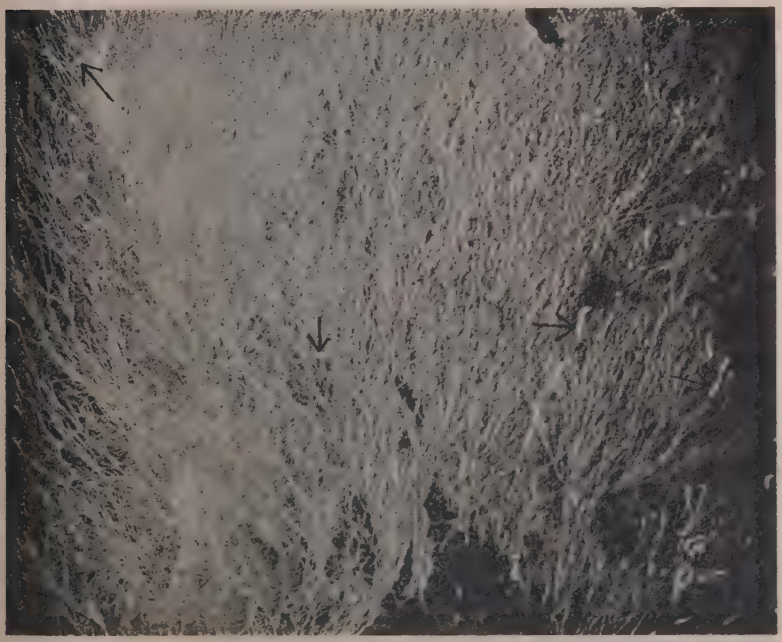

Plate XX.—Larvae of tiny gnats feeding upon root-rot strands in the soil. x1.

the process was reversible on further selection, suggesting a heterogeneous condition of the original material. Neal (77) found that cultures lost their vigor and ability to produce strands and sclerotia in culture. King, Loomis, and Hope (59) find their cultures variable in vigor and production of sclerotia and suggest that the cultures may decline in vigor after being maintained in the laboratory for many months. Our own cultures have shown variations in ability to produce sclerotia and to infect plants, but the degree of permanence of these variations is not known.

INSECT RELATIONS

We have noted in unsterilized soil cultures of the root-rot fungus that certain tiny insect larvae feed copiously on the fungus strands (Plate XX) to the extent that in some cases all fungus growth disappears. These tiny maggotlike larvae mature and emerge as very small gnats[7] and are probably just one of a number of natural enemies of the root-rot fungus and which may at times limit its spread.

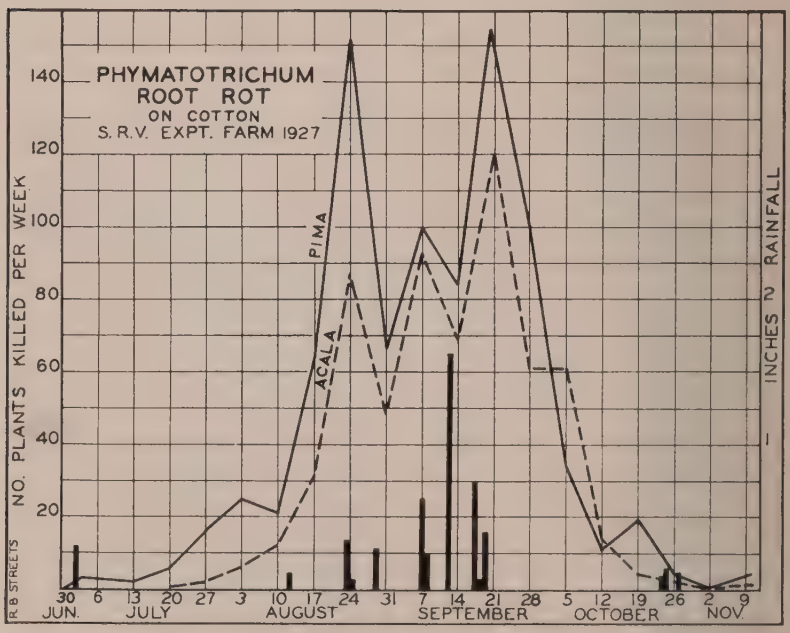

Figure 5.—Seasonal occurrence of root rot on Pima and Acala cotton during growing season of 1927. The smaller number of plants killed in the period from August 31 to September 14 was due to an irrigation on August 26, followed by a period of rains and higher humidity.

[7] Identified by L. P. Wehrle of the Entomology Department, University of Arizona, as belonging to the fungus gnats (Family Mycetophilidae).

PERIOD OF ACTIVITY

Root rot is most destructive during the months of August and September but is prevalent from early in June to the end of October. During this period the soil temperatures are favorable to the development of the fungus, and soil moisture is the principal factor determining the severity of the disease. Since plants in the areas subject to root rot in Arizona are almost universally grown under irrigation and the usual practice is to keep the soil moderately wet, ideal conditions for the spread of root rot are maintained.

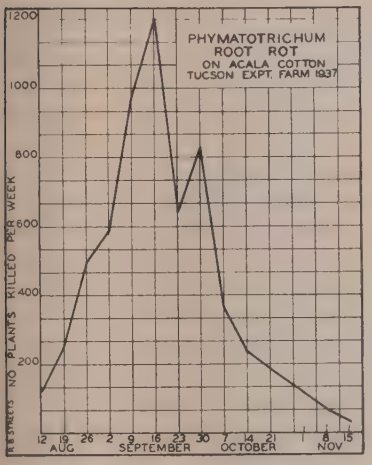

Figure 6.—Seasonal occurrence of root rot on Acala cotton at Tucson, Arizona. This graph shows a late but severe infection with the greatest number of plants killed in mid-September.

While the most destructive period is from June to October inclusive (Fig. 5), the fungus is more or less active in our soils throughout the year. Where moisture conditions are favorable, the activity of the fungus depends largely on the soil temperature. This activity is most evident in trees or other perennials infected late in the summer and slightly if at all visibly damaged at the beginning of cool weather. Such trees or plants often die in the spring before the onset of summer temperatures. In mild winters, like the one experienced in 1934-35 in Tucson, susceptible trees died throughout the fall and spring months, and a few even succumbed in January and February, although this condition is rare.

The activity of the fungus has been followed through the winter on the roots of cotton which survive the winter even after the tops have been killed by frost. Infection spreads to previously healthy cotton roots, but the rate of spread during January and February is only one tenth of that during August.

Figure 6 shows a typical curve of seasonal activity of root rot in the Tucson area where the disease becomes destructive later in the season.

LIFE HISTORY

METHODS OF SPREAD

By strand growth along roots

The root-rot fungus progresses from one host plant to the next principally by growth of the strands along the infected roots and through the soil until they come in contact with other susceptible

roots which they envelop and penetrate (147b). It is this slow, steady, inexorable advance through the soil which is responsible for its destructiveness, and the necessity of destroying it in the layers of soil below the plow sole makes it difficult to control.

By strand growth through soil

The distance which the strands can grow through the soil independent of plant roots appears to depend principally on the available food supply and temperature. King (57, 59) found that the fungus grew through moist sand for 2½ feet with an average daily growth of over ¾ inch and a maximum growth of 1½ inches in a day. A short piece of root-rot-infected cotton root furnished both inoculum and food supply for this experiment. The rate of growth, about 12½ feet in five months, agrees with the advance often observed under field conditions.

By soil from infected areas

Soil from infected areas might easily spread root rot to other soils (60) principally on account of the infected roots and sclerotia which it might contain. Taubenhaus and Ezekiel (139) were able by screening infected soil to remove the roots, and cotton grown in the screened soil did not become infected, although the cotton in unscreened soil developed the disease. Our own experience has been that soil from root-rot areas often fails to transmit the disease to plants grown in it in greenhouse benches, large clay pots, and glass-sided root-study boxes. There is, however, enough danger of spreading root rot by means of such soils to make their use unwise.

By nursery plants with or without soil

Plants with a ball of dirt on the roots from an infected area are far more certain to transmit root rot than soil alone. The roots of apparently healthy plants may be slightly or to a considerable extent infected by the root-rot fungus, or the fungus may be in either active or dormant form in the ball of soil (147f). The appearance of root rot in a locality outside its natural range was traced to the planting of trees and shrubs from infected areas. For the above reasons it is essential that land used for nurseries or plant propagation be free from root rot on account of the great danger of spreading the disease in distributing and transplanting in uninfected soil.

Root rot frequently appears on trees and shrubs in city yards where all irrigation water originates from deep wells and is applied through garden hoses.

By cultural practices to a limited extent

While root rot may be occasionally carried by any mechanical means which would move pieces of soil, infected roots, or sclerotia, twelve years of observation and experience with the disease has convinced the writer that these accidental mechanical carriers

are not important under irrigation, and that the fungus is not ordinarily distributed by tillage implements and cultural practices or irrigation water. McNamara and Hooton (65) find no evidence that infection is spread by tillage implements or on the feet of work animals. Infected areas in cotton and alfalfa spread about as fast across the rows as along the rows and about as fast against the flow of water as in the direction of flow. In the case of trees evenly spaced in a row and watered by a single ditch, the progress of the disease is about equal in both directions from the original center of infection.

The sudden appearance of root-rot spots in a field thought to be free from disease has been noted time and again, and might be cited as evidence of mechanical carriers or spread in irrigation water. Against this can be cited an experimental field which the writer has used for the past nine years and had under observation for three years previous to that. Root rot has always been very severe on the upper end of the field and practically absent on the lower one third. Leveling the field from end to end of the rows by a transfer of soil from the upper infected end last year has failed to increase appreciably the infection at the formerly low end.

By floods and erosion

It would appear highly probable that the root-rot fungus could be readily spread by the natural processes of erosion accompanying heavy rainfall, either by means of sclerotia which are produced to some extent in the upper 6 inches of soil or by infected roots or sclerotial strands. Interesting data on this problem are presented by Rea (147f, g) from erosion studies on infected plots at Temple, Texas. A 4-inch rain removed over 1½ tons of soil, but no sclerotia were found in the samples taken of this soil. A heavy rain the following spring caused gullying to a depth of 8 inches but again no sclerotia were recovered from soil and water samples. The fact that most of the sclerotia in these soils were found at a depth of 12 to 36 inches may account for the results secured.

The observations of Peltier (94, 95) in the shelter belt zone in Texas suggest that over long periods of time erosion may be an important factor in the spread of root rot, for he finds that when root rot is found at the headwaters of a stream it is usually distributed throughout the drainage basin and its incidence increases at the lower levels. The writer has made similar observations on many of the tributaries of the Gila-Salt River system. In the absence of cultivated fields it has been difficult to determine the upper limits of the infection, but root rot has been found at levels above 3,500 feet along the Santa Cruz, San Pedro, Gila, and Verde rivers and their tributaries.

Not spread by spore mats or insects

There is no evidence that the spore mats are ever concerned in the spread of root rot.

Efforts to recover the root-rot organism from fecal pellets of insects fed on infected cotton plants and root-rot strands failed (127, 128), so it appears that cotton-feeding insects do not spread the disease.

RATE OF SPREAD

Since the normal spread of root rot is by means of strands of the fungus growing along infected roots and through the soil, any conditions which would influence the rate of growth of the strands, such as soil temperature, moisture, porosity, and reaction (*p*H) of the soil, and availability of food supply (spacing, root habits, and susceptibility of plants growing in the infected soil) determine the rate of spread of root rot.

In alfalfa fields the usual rate of advance of root rot is from 2 to 8 feet per month, the higher rates occurring only in midsummer or in new stands of alfalfa. In southern Arizona alfalfa is planted in September or October, but no plants are lost from root rot until the following summer. An experimental field planted on heavily infected soil showed no sign of root rot until June, but the disease spread rapidly and by September the stand was ruined in the infected areas.

In cotton fields the infection may spread during the season from 5 to 30 feet from the original center of infection. Cotton being an annual plant requiring fairly high temperatures, the root system does not occupy the soil and come in contact with the root-rot fungus early in the growing season. At Tucson June 25 is the average date of the first appearance of root rot in cotton, although it is usually some two weeks earlier in the lower valleys where the season is more advanced.

The spread of the disease in plantings of fruit and shade trees and other ornamentals is variable depending upon the spacing of the trees or shrubs and their susceptibility to root rot. In the case of apple, pear, peach, or other deciduous fruits spaced from 20 to 25 feet apart, many observations have shown that the usual advance is about 25 feet per year—that is, the tree adjacent to the last dead tree will succumb during the next summer or fall. Where shade trees planted in a row lose a tree from root rot, the rate of progress is similar. Where the spacing between trees is as much as 40 feet, the second tree may not develop root rot until the second year.

A number of instances in which the disease seemed to cross a city street, sometimes a paved street, jumping a distance of 60 to 80 feet, may perhaps be more logically explained as the result of two independent centers of infection.

METHODS OF OVERWINTERING

In living roots

The fungus very commonly overwinters as mycelium (fungus filaments) in and on the roots of living susceptible plants. Woody

plants such as trees and shrubs may be attacked too late in the summer to be killed that season, and the fungus passes the winter in a more or less dormant condition, resuming active growth in the spring when soil temperatures become favorable again. A similar condition is found in the case of perennials like alfalfa and also in cotton grown in this state, as most of the roots survive the winter. In Texas (139) the root-rot fungus was found to survive and spread slowly on the living roots of cotton, okra, pepper, sweet potato, carrot, beets, susceptible shrubs, fruit and ornamental trees, and the fleshy roots of the pink-flowered wild morning glory.

Studies by Taubenhaus (126) in south central Texas showed that the fungus was able to survive on fourteen different winter and spring weeds normally found growing in fallow fields and in fields devoted to permanent cotton or to corn.

In dead roots

While the root-rot fungus cannot ordinarily be isolated from the dead roots of plants more than a week or two after the death of the roots themselves, there is evidence that the fungus occasionally survives for indefinite periods in deeply buried tree roots. One such instance is cited by Ratliffe (98) in which a persistant root-rot infection which reappeared in the same spot in spite of a five-year rotation with nonsusceptible crops was traced to the roots of a mulberry tree which had died from root rot and had been removed. The fungus was recovered from the roots at a depth of 5 feet from the surface. Cultures of recently killed roots, however, show that in most cases the dead tissues are promptly invaded by a great variety of soil inhabiting organisms, some of which are antagonistic to the root-rot fungus.

As sclerotia in soil

The small tuberlike sclerotia which are produced most abundantly by the fungus in the early fall months are well adapted to survival of the winter months in a dormant condition (see page 344 and Plate XVIII). On the return of favorable temperatures they germinate and send forth strands which can infect susceptible roots.

As strands in soil

While the individual strands are usually relatively short-lived in the soil, certain strands may develop thickened walls and become in effect sclerotial bodies, and as such persist in a dormant condition in the soil until favorable conditions for growth return (10, 69).

GROWTH CYCLES IN ROOT-ROT SPOTS

It was early observed that root-rot infection varied in intensity from year to year in the same field, but the first detailed maps of infected plots were published by Scofield (107) in 1919. Since

mapping offered an excellent opportunity to study the life history and behavior of the fungus and the effectiveness of control measures, it was generally adopted by investigators, and a series of maps have been published by King (46), King and Loomis (55, 56), McNamara (63, 66), McNamara and Hooton (65), and finally an elaborate series covering seventeen years' observations at the San Antonio field station by Ratliffe (99).

Maps of plots at the Greenville field station (66) for the nine-year period, 1920-28, are typical and show that the root-rot spots pass through a period of sustained growth for from three to eight years, and then in a single season undergo a disintegration, or breaking up, of the infected area into a few small isolated points and the cycle starts over again. A more gradual breaking up of infection than occurs at Greenville has been described by King and Loomis (55, 56) as occurring at Sacaton, Arizona.

Many explanations have been offered to account for growth cycles but no entirely satisfactory theory has thus far been advanced. Root-rot spots apparently behave independently of cultural and climatic conditions, and spots in the same field behave independently of each other. Some spots break up in wet years, some in dry years, and adjacent spots which have grown together have in later years broken up separately, and spots developing normally are nearly always found near those which have broken up. Our present knowledge is insufficient to explain this cyclic behavior, but it may be due to the fungus itself passing into a semidormant condition or to the ravages of some natural enemies, microorganisms, or insects.

The writer has often noted, as have Ratliffe (99) and others, that root-rot infection is inherently more prevalent and active in certain well-defined areas than in other adjacent areas. The disease, Ratliffe found, spread rapidly in some areas, was present but spread little in others, and did not occur at all in certain areas during a seventeen-year period.

Taubenhaus and Ezekiel (139, 146) advance the theory that the periodic cumulative increases of root rot in certain highly favorable soils, such as the Houston black clay, usually followed by abrupt decreases for several years, is due to the rapid infection and decay of roots early in the season with resulting death of the vegetative strands leaving relatively few undecayed roots on which the fungus can overwinter in a vegetative condition.

PATHOGENICITY

METHODS OF INOCULATION

For over thirty years following the discovery that root rot was caused by a fungus workers were confined to field observations, since no satisfactory method of inoculating plants with the organism had been devised, and without doubt progress in the understanding and control of root rot was greatly impeded. Unsuccessful attempts to obtain artificial inoculations are recorded by Pammel (92) in 1890, Duggar (16) in 1916, and Taubenhaus and

Killough (148) in 1923. The inoculum used included (1) diseased roots fresh from the field, (2) pure cultures from diseased roots, (3) fresh conidia from spore mats, and (4) soil from root-rot spots.

In 1922 King (45) successfully inoculated cotton plants by digging a trench between two rows of cotton plants and carefully digging away the soil until 15 inches of each taproot lay exposed in a narrow vertical channel. One-inch pieces of root-rot-infected cotton roots were placed end to end paralleling and in contact with the healthy root and the channels filled with sterile cotton soaked in distilled water, and the whole was covered with soil saturated with water and applied with a trowel. The inoculated plants began to wilt and die in twelve days, and later the fungus spread through the soil to uninoculated plants. Taubenhaus and Killough (148) successfully inoculated the roots of cotton plants growing in bottles of sterilized soil using pure cultures of *P. omnivorum*. Peltier, King, and Samson (93) prepared inoculum by growing the fungus in a sterilized mixture of sand and cotton roots in 2-quart Mason jars. Cotton and alfalfa plants were inoculated in the field by breaking the jars and burying the contents intact between the rows at a depth of 8 to 10 inches and keeping the soil moist. They secured infection only where the inoculum was in direct contact with cotton roots.

A much easier and quicker method satisfactory for extensive use in field and laboratory was published by the Texas investigators (130) in 1930 and has proved of great value in securing data on the relative susceptibility of many plants to root rot, as well as for other purposes. The roots of plants freshly wilted from attack by the root-rot fungus furnish the most satisfactory type of inoculum, as they supply the organism in its most virulent form. This material can easily be secured in abundance on the margins of root-rot spots and during summer and fall months when root rot is most active, and it can be stored for several days if kept moist and in a cool place. A crowbar or other instrument is used to make a hole in the soil 1 to 1½ inches from the stem of the plant to be inoculated. One or more pieces of inoculum are placed in the hole and soil pressed together again. The success of this simple method depends upon two factors: the inoculum must lie close to the host root and parallel to it (in this position it is usually at some point in actual contact with a lateral root), and the soil moisture content must be relatively high. (Apply water to inoculated plants or irrigate after placing inoculum unless soil moisture is adequate.) We have found it desirable to place the inoculum 4 to 6 inches below the surface instead of 2 inches as recommended in order to avoid the effects of rapid drying of the surface soil. In midsummer the first above-ground symptoms appear on cotton in ten to fourteen days, and inoculated plants are usually killed within thirty to forty days.

METHOD OF INFECTION

Point of initial infection

The usual point of infection in crops like cotton and alfalfa is given by most workers as the root zone between 6 and 18 inches below the soil surface (82, 93, 148). This is the zone in which the development of lateral roots is the greatest. Many plants are found in which infection has traveled along a lateral root to the taproot or attacked the taproot directly leaving the living upper and lower portions of the taproot separated by a zone of infected tissues. Our studies of infection in cotton and alfalfa plants show that point of infection is variable, however, and that frequently the lower portions of the taproot are the first to become infected, suggesting that the fungus is traveling laterally in deeper layers of the soil. The appearance of new centers of infection late in the summer can best be explained by the presence of deep-seated infections which occur about midsummer and cause no visible injury until they have advanced along the taproot almost to the surface of the soil (Plate XXI).

Plate XXI.—An apparently healthy alfalfa plant growing 2 feet outside the margin of a root-rot-infected area. The taproot has been killed by root rot to a point 4 inches below the soil line and the plant is being supported by the healthy fibrous lateral roots. x⅛.

In the case of trees or shrubs infection apparently starts on the lateral roots on the side exposed to the root-rot infection, and frequently a tree will show clearly a one-sided infection (Plate XXII).

Method of penetration

The strands of the root-rot fungus grow through the soil and on coming in contact with the root of the susceptible plant envelop it with a mantle of strands (Plate XXIII), which become smaller and branch fanwise into individual filaments at the advancing margin.

In places along the side of the strand touching the root the fungus cells form an intimate contact with the root cells. As growth proceeds the fungus cells wedge between the host cells,

Plate XXII.—Apricot tree with one limb showing effects of root-rot infection on roots underlying that side. Photographed in June. The tree died that fall.

penetrating several layers of cortical cells in this manner (Fig. 7). From this point on, the fungus appears to be able to penetrate the host cells freely, and further progress through the cortex and woody cylinder and into the thick-walled xylem cells (water ducts) is from cell to cell rather than between the cells.

Watkins (153) has recently studied the penetration and invasion of the roots of cotton seedlings grown in nutrient agar. The roots are rapidly overgrown with a mycelial weft, and sections show that individual hyphae may penetrate the epidermal cells or root hairs. From the epidermis the hyphae grow through and between the cells of the cortex, penetrating the endodermis and stele,

Plate XXIII.—Root-rot strands on four-o'clock. The strands on above-ground portion of stem developed in moist chamber. x1.

where longitudinal growth in the vascular elements was observed. No definitely organized haustoria were observed. The invaded cells were finally killed. All these stages of penetration with exception of root-hair infection had already been observed in the watermelon by Butler (8).

The fungus appears to attempt entrance at many points on the same root almost simultaneously, which accounts in part for its success in invading its many host plants. Alfalfa may show this condition of multiple infection as in Plate XXIV with many small lesions, usually at the point of emergence of small lateral roots.

Once within the root tissues, the fungus travels in both directions killing the cortex and invading the central woody cylinder. The fungus as a rule does not invade the plant tissues above the soil line, although discoloration of the woody tissues is commonly found associated with root rot. The strands, however, will envelop the above-ground tissues as shown in Plate XXIII where strands arising from the infected root of the plant of four-o'clock grew over the green stem in a moist chamber.

Period from initial infection to appearance of symptoms

The time elapsing between initial infection and the development of characteristic symptoms above ground depends upon many factors such as: susceptibility of host, size of host plant, position of infection (on unimportant lateral, on taproot near crown, etc.), and temperature and moisture conditions.

On seedlings in artificial culture media.—Several investigators have studied the penetration of the fungus into the roots of seedlings growing under admittedly artificial conditions. Taubenhaus and Ezekiel (147e) inoculated cotton seedlings grown aseptically

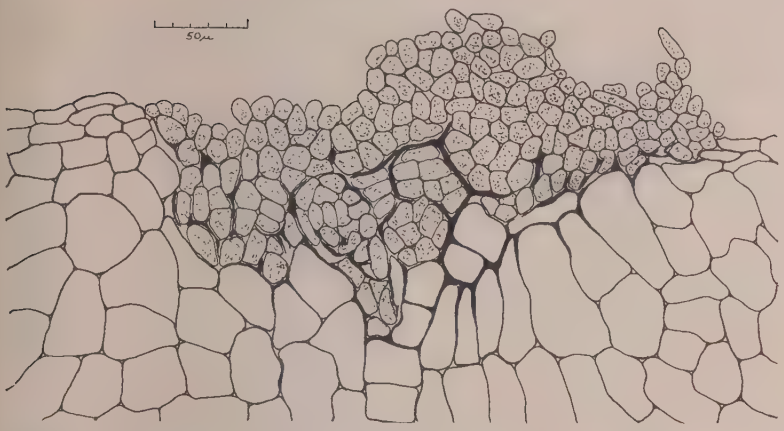

Figure 7.—Detail of infection of alfalfa root by the root-rot fungus. Cross section of alfalfa root showing cells of fungus wedging between host cells and also invading them. Camera lucida drawing. x600.

Plate XXIV.—Roots of one-year-old alfalfa plants from border of root-rot area showing numerous small sunken lesions. Healthy root at right. x⅓.

in tubes of agar and found the fungus in the outer layer of epidermal cells after five days, in the parenchyma after eight days, and in the vascular system and pith after twelve days. Butler (8) observed that watermelon seedlings exposed to pure cultures of *P. omnivorum* on agar at 82 degrees F. had the roots enveloped by the fungus especially near the tip in twenty-four hours and that some wedging action had begun, and that actual penetration had taken place in forty-eight hours. Seedlings grown in sterilized soil inoculated with the root-rot fungus developed brown lesions on the roots in ten days, and half of them died on the twenty-fifth day.

On plants in the field.—Eaton and King (17) find that at least six weeks elapse between infection and the first appearance of symptoms on cotton in the field. In the case of pecan and some others of the more resistant trees, the writer has observed as much as a year may elapse before above-ground symptoms appear.

Often the very susceptible pepper tree standing next to a dying tree will show no signs of disease (Plate IV), although the roots on examination will usually be found to be already infected.

RESISTANCE AND IMMUNITY

The fact that no monocotyledonous plant has yet been found definitely susceptible to Phymatotrichum root rot while over 1,700 species of dicotyledons and gymnosperms (conifers) are known to be susceptible naturally raises the question of why monocotyledonous plants as diverse as palms, Johnson grass, onion, gladiolus, and corn should be immune and dicotyledons as diverse as cotton, sweet potato, carrot, Chinese elm, and castor bean should be susceptible. Such a difference might be due to some morphological features, which prevent infection and growth in the resistant plants or to biochemical conditions favoring growth of the root-rot fungus in susceptible plants or inhibiting it in resistant plants. A series of studies on the nature of resistance of monocotyledons to root rot by Ezekiel, Taubenhaus, and Fudge (31, 32, 34, 138, 140) offers a partial answer to this problem.

The undiluted juice from resistant (monocotyledonous) plants (corn, onions, cannas, and nut grass) was found to partly or entirely inhibit the growth of the root-rot fungus, while the juice from susceptible (dicotyledonous) plants (cotton, carrots, and sweet potatoes) supported profuse growth. Upon dilution of the juice from monocotyledons with distilled water, the inhibition appeared to be mostly removed, suggesting that the failure to grow on undiluted juice can scarcely involve lack of essential nutritive material but appears to involve the presence of some specifically inhibitory material in the resistant plants (31).

Continued studies (32, 34) directed toward the isolation and identification of these toxic substances, were carried out with fractions of juices, concentrated under reduced pressure and added to nutrient solutions. Ether extracts from the juices of monocotyledons were invariably toxic, while ether extracts from dicotyledons were not. In both cases the aqueous residues were toxic but were present in comparable amounts in the concentrated residues and are presumably not involved in the immunity of monocotyledonous plants. Purified fractions of the toxic material completely prevented growth when less than 0.05 per cent of plant material was added to the nutrient solutions. It seems probable (34) that immunity of monocotyledonous plants is due, at least in part, to relatively high concentrations of these specific ether-soluble materials of an acidic nature in the plant roots. The exact chemical nature of these substances is at present unknown.

CONTROL MEASURES

Root rot has proved to be one of the most difficult of all plant diseases to control. Although the disease was recognized in 1888, the only successful method of control was rotation with non-

susceptible crops. Only within the last decade, during which the disease has been studied intensively, has our knowledge been advanced enough to show progress in the development of several other promising lines of attack.

The root-rot fungus presents such variable and erratic behavior in different sections and even in the same field in different years that it has been impossible to predict accurately its behavior under any specific set of conditions, which prevents the laying down of very precise and dependable control measures. It is especially noteworthy that the response to certain treatments such as manuring is more favorable under irrigation than where crops are grown under natural rainfall. There is likewise some evidence that the behavior of the fungus in the soils of northeastern Texas is different than in the other sections of the same state.

ROTATION WITH NONSUSCEPTIBLE CROPS

Rotation with crops not subject to root rot is still the most satisfactory and economical method of combating root rot in large fields, especially where the value of the land and the crops grown on it limit the amount of money which it is practicable to spend on eradication. The chief limiting factor in making use of rotation is the difficulty in arranging a satisfactory rotation. The returns from resistant crops such as small grains, grain sorghums, and corn are much less per acre than for cotton and alfalfa. Likewise the grower may be lacking in equipment and experience necessary to raise these crops or such specialty crops as the resistant asparagus, cantaloupes, onions, and winter vegetables. The grower must also consider the prospects of marketing these crops at a profit. In spite of these difficulties, rotation offers the most promise of returning infected acres to profitable production, and the grower must make some sacrifices to attain that end.

Years of experience in several states have shown that in most cases (99, 108) a two-year rotation is of little value, a three-year rotation shows some reduction in root rot, and a four-year rotation greatly reduces but does not always eliminate root rot. During the three years which the infected area is kept in nonsusceptible crops, special attention must be paid to keeping down all susceptible weeds or volunteer plants which would keep alive the root-rot fungus.

CLEAN FALLOW

Plowing root-rot-infested land and cultivating it as often as necessary to keep down all susceptible weeds has given variable results but on the whole has not been encouraging. Fallow seems to be no better than a clean cultivated nonsusceptible crop for eliminating root rot, and the grower loses the use of the land. Since all the lands under cultivation in parts of Arizona where root rot occurs are irrigated, the idle land in most cases carries relatively high fixed charges for water and taxes (amounting to

about $20 per acre annually), so the loss of use causes a greater loss than in areas depending upon rainfall.

In experiments at San Antonio, Texas (99), where the annual rainfall is about 27 inches, root rot persisted and spread as effectively when cotton was planted on alternate years and the soil fallowed for seventeen months as when cotton was planted every year. Tests at Sacaton, Arizona, on fine sand and silt under irrigation (46, 57) fail to show reduction in root rot from either one- or two-year fallow.

Results with fallow appear to be unpredictable: twenty-four months' fallow on Houston black clay (147c) at Temple, Texas, gave practically no reduction in root rot, while the same fallow period at Greenville, Texas (63), eradicated the disease in one plot. Extensive tests by Rea (100), in which the amount of root rot in cotton following weekly listing to a depth of 6 inches during the winter, during the summer, for twelve months, and for twenty-four months was compared with adjoining plots in continuous cotton, showed a great reduction in root rot under the longer schedules. Excavations in plots where considerable root rot survived showed the presence of many sclerotia, probably formed before the test started.

OTHER CULTURAL PRACTICES

Deep fall plowing was recommended in 1907 (110, 111) and in 1921 (37) as a control for root rot in combination with rotation. Later reports in 1923 (148) indicated that deep plowing was of little value, but more recent tests are considered to be promising. The writer attempted a number of years ago to eradicate root-rot from several acres of land by deep fall plowing, and by subsoiling followed by pulling and burning the cotton roots (114). In each case the treatment seemed at first successful, as no root rot appeared in cotton the following season until late, the middle of August, and the loss from root rot was very slight. The late infection probably arose from deep seated centers of infection. Fall plowing and subsoiling should be considered as a means of reducing, but not eradicating, root rot and is not certain of success in all cases.

Why cultural practices fail

The basic reasons why rotation, clean fallow, fall plowing, subsoiling, and other cultural practices have failed to produce the results expected of them are: (1) The root-rot fungus does not as formerly believed (148) require the living roots of susceptible crops in order to survive in the soil. (2) The roots of susceptible plants remaining undisturbed in the subsoil below the depth reached by cultivating tools do not die quickly but may survive many months. We have found living roots of cotton and alfalfa in June following fall plowing, providing a food supply for the fungus. (3) The fungus may live for a number of years at least on dead, deeply-buried roots of susceptible plants. (4) Some of

the sclerotia (resting bodies) of the fungus may lie dormant during the period of rotation or cultural treatment.

Flooding

It has long been known that root rot does not thrive on land subject to periodic overflow by floodwaters, so in 1928 and 1929 experiments on the deliberate flooding of infected fields were conducted in the Yuma Valley (114). In order to secure additional water to replace seepage and evaporation, sites were chosen near one of the smaller canals, but a combination of sandy soil, gopher holes, and adjacent borrow pits bordering the canal resulted in a number of breaks in the levees; so flooding was not continuous. In each field flooded from sixty to ninety days the amount of the disease was reduced, but eradication was not secured.

Similar experiences with flooding for various periods up to six and one half months in Texas (137, 147f, g) and the discovery of the sclerotia which may remain viable for long periods under water (48) indicate that flooding cannot be relied upon to secure eradication and is not worth the trouble and expense involved.

SELECTION AND BREEDING OF RESISTANT VARIETIES

While the possibility of finding or breeding resistant strains of our most important crop plants and ornamentals is the greatest hope for the future, progress in this direction will be slow and difficult. It is at present impracticable to attempt breeding and selection in all of the two hundred and fifty-odd species of cultivated plants known to be susceptible to the root-rot fungus. Efforts to date have consisted principally of testing as many as possible of the varieties of some of our principal crop plants such as cotton, apple, grape, pear, cowpeas, soybeans, peanuts, okra, and plum. While the data, except in the case of cotton, are too meager to permit definite conclusions, there appears to be no marked difference in the susceptibility of different varieties within the same species, except in the case of grape, plum, and citrus. The grape varieties, Champanel, Mustang, and Black Spanish, appeared resistant, and *Vitis champini*, *V. constancia*, and *V. cinerea* offered promise as rootstocks in extensive tests at the Weslaco, Texas, substation (147e, g, h). These varieties have not been tested for adaptation to Arizona conditions. In the same experiments the sour orange rootstock was found to be highly resistant, while the Cleopatra rootstock and orange, grapefruit, tangerine, and lime on their own roots were very susceptible. Fortunately, the susceptible rootstocks are rarely used in Arizona, and in only two instances has root rot been found attacking citrus trees in this state. The Marianna plum sometimes used as a rootstock in the Southwest has been found resistant to root rot, but has not been tested for Arizona conditions.[8]

[8] The following information is quoted from a letter from E. Mortensen, Superintendent of Substation No. 19 of the Texas Agricultural Experiment Station at Winterhaven, Texas. "The Marianna plum is a vigor-

A large number of varieties of cotton and selections of individual strains have been tested for possible resistance in Texas (138), and all have been eliminated as susceptible except a few which are still under test. Experiments begun at this station in 1927 with a hundred plant selections of Acala and the same number of Pima cotton (the principal varieties grown in Arizona) have given somewhat more encouraging results. Plant selections were made at the end of the growing season in the most heavily root-rot-infected parts of commercial fields grown from high-grade seed. The plants selected in most cases stood alone in the midst of dead plants often being the sole survivor in an area 1 or 2 square rods in extent. Surviving plants were dug and the root systems examined. While a few plants showed no infection of the root system (Plate XXV), a small number showed slight infection, and the balance moderate to severe infection. Only the most promising were saved and planted on infected soil next spring. Most of the selections were discarded after two years' test and only the best saved for further testing and elimination. As is the case in the field the Pima selections were somewhat more susceptible than those of the Acala variety. No highly resistant strains were found in either variety but the selections showed considerable variability in height, earliness, yield, and resistance to root rot. Plants of each selection were self pollinated for several years in order to eliminate the effect of cross-pollination. The best strains are still under test, but the degree of resistance attained is difficult to measure on account of the erratic behavior of the disease which gives widely divergent results in replications grown under apparently identical conditions. The development of strains of cotton resistant to root rot remains for the present in the experimental stage.

One variety of cotton has been found, however, which will produce a satisfactory yield on root-rot-infected land. Stoneville cotton under our growing conditions produces a high percentage of its crop of bolls early in the season, and one half or more of the total yield is secured at the first picking. The early maturity of this variety avoids the usual heavy losses in yield, as the crop is largely matured before the period of greatest mortality to the cotton plants arrives. Against the satisfactory yield must be cited the fact that Stoneville cotton will usually grade one grade lower than Acala or Mebane as the lint is shorter and the hairiness of the leaves and bracts makes it difficult to pick clean of leaf fragments and trash. Stoneville cotton has been grown pricipally in the Yuma Valley.

Alfalfa plants surviving in root-rot-infected areas are nearly always found to be existing by means of lateral roots after the primary taproot has been killed (plates X and XXVI).

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ous hybrid that has been used for some time by Texas nurserymen as a stock for plums. It has not been very successful as a peach stock because of poor union. . . . Marianna plum is propagated by cuttings . . . is not entirely resistant but does seem to be more resistant than Myrobalan and is certainly much more resistant than peach stocks."

Plate XXV.—Mature cotton plant taken from a badly infected area. Plants of this type are used as a basis for selection for disease resistance, but a very large per cent of them fail to show any marked degree of resistance. x⅛.

Plate XXVI.—Three alfalfa plants which survived attack by root rot the first year but died the second year, indicating lack of true resistance. x½.

SOIL DISINFECTION

The disinfection of soil by heat or chemicals is effective, but decidedly limited in application on account of its cost and the difficulties of adapting it to field conditions. It is practicable only where the results justify the cost, for example, where small areas can be treated to prevent the spread of root rot to large fields or valuable plantings, such as orchards, nurseries, or ornamental planting, or where small amounts of soil are to be treated for propagation work in plant beds, greenhouse benches, or for potting soil.

Formaldehyde

One of the first chemicals to be used successfully against root rot out-of-doors was formaldehyde (44, 45, 46, 50, 71, 73). One and one quarter gallons of 40 per cent formalin diluted to 100 gallons with water and applied at the rate of 1 gallon per cubic foot of soil will eliminate the root-rot fungus and other soil-inhabiting plant pathogenic fungi. Unfortunately, this solution is also lethal to plant roots and cannot be safely used within 20 feet of trees and shrubs, as the formaldehyde gas is decidedly volatile and diffuses rapidly through the soil. The use of formaldehyde solution to treat infected tree holes in city yards has sometimes resulted in defoliation of trees and shrubs near by within a few days after treatment. Where injury was not too severe the affected plants recovered. To be effective against root rot the soil should be wet to a depth of 4 feet, or in the case of trees to a depth of 6 feet, requiring an application of 4 to 6 gallons per square foot respectively, as 1 gallon is required to wet a cubic foot of average soil. Formaldehyde possesses the advantage of being volatile and leaving no harmful residue in the soil but offers no protection against reinfection of the soil. In spite of its toxicity to living plants and high cost (about $2.25 per gallon, retail), formaldehyde is useful in a limited way in the control of root rot.

Carbon bisulphide

This highly volatile, heavy liquid is an excellent fungicide, but its usefulness is limited by its costliness (about $1.00 per gallon, retail), making the cost of treatment about $1.00 per square rod, and by fire hazard (72). The liquid must be handled with the same precautions as gasoline as it is inflammable, and the gas which is heavier than air is explosive. The fumes are toxic to man but are so unpleasant that there is little danger if the carbon disulphide is handled out-of-doors. The container must be kept in a cool place. Carbon bisulphide is used undiluted, 2 to 4 ounces being poured in holes 6 to 12 inches deep made with a crowbar and sealed promptly with moist soil. The holes should be 18 inches apart each way. To be effective the chemical must be applied to fairly moist but not wet soil and the surface sealed to prevent escape of the gas by a very light watering or a gas-proof cover of fabric or paper. Like formaldehyde carbon bisulphide cannot be

safely used within 20 feet of trees or shrubs. Unsatisfactory results were secured at Sacaton (56) when 3 acre-inches of 1:100 solution of carbon bisulphide in water were applied in basins.

Steam sterilization

One of the cheapest and most satisfactory methods of sterilizing soil is the use of live steam, although in practice the method is restricted to treating soil for potting, greenhouse benches, and plant beds (42). The equipment in addition to the boiler necessary to produce the steam—and this can be the regular heating equipment—is very simple, consisting of a bin to hold the soil to be treated and a grid of pipe perforated to insure even distribution of steam and a connection to the steam line with a shutoff valve (115). Soil treated with steam by this method rises in temperature almost to 212 degrees F., and the temperature at the surface covered only by an old blanket is about 203 degrees F.

Not only the root-rot fungus but the root-knot nematode, fungi causing damping-off of seedlings, and all insects and weed seeds are destroyed by steaming of soil. Care should be taken in handling sterilized soil to avoid recontamination.

Electrical pasteurization

Two methods for the partial sterilization of soil by the use of electricity have very recently been proposed (89). The first method involves the use of electrical current passing through moistened soil between two electrodes; the second method uses resistance heating elements to bring the soil to the required temperature. Since the first method depends upon several variable factors, such as moisture content and conductivity of the soil, and involves some risk to the operator from coming in contact with the electrodes, the second method seems preferable. In both methods the soil is brought to a temperature of 140 degrees F. which is sufficient to destroy all undesirable organisms and yet not completely destroy the normal soil flora and set up undesirable changes in the organic matter in the soil. Electrical pasteurization is inexpensive, as the current consumption in either method is about 1 kilowatt per cubic foot of soil. At 3 cents per kilowatt this brings the cost per greenhouse flat to ½ cent (per gallon can, ¼ cent). The equipment is relatively simple and inexpensive. Details will be furnished to those interested upon request.

Volatile organic compounds

A great variety of chemicals, among them many volatile organic compounds, have been tested by Taubenhaus and Ezekiel (24, 27, 28) against the root-rot fungus. They report tetrachlorethane, pentachlorethane, and xylol, solvents used in industry, as very toxic to the fungus when applied to soil. The toxicity, however, extends to plant roots as they find the chemicals too toxic to woody perennials to warrant their use in treating infected fruit trees and ornamentals (28, 147h).

Crecylic acid

King (56) found that a 2 per-cent solution of crecylic acid was definitely toxic to the root-rot fungus, but the chemical has never been used extensively in controlling root rot.

Organic mercury compounds

A number of organic mercury compounds, developed as fungicides for the treatment of seeds and control of seedling diseases and marketed under trade names such as Semesan and Uspulun, have proved quite effective in laboratory and limited field tests but are too expensive for use in the generous amounts required to stamp out root-rot infections. The ¼ per-cent solution in water is satisfactory for limited use. The duration of the fungicidal action of these complex compounds in the soil is not known, but it is probably much longer than that of the volatile fungicides.

Sulphuric acid

Experiments have shown that solutions of sulphuric acid (1 to 5 per cent in water) are toxic to the root-rot fungus (114), but difficulties arise in attempting to apply such chemically active solutions to our alkaline-calcareous soils. The solution promptly reacts with the surface layers of the soil and the acidity is quickly neutralized, and little or none of the acid reaches the deeper layers. This condition was overcome in some experiments on small infested areas by making holes 18 to 30 inches deep with an iron bar before applying the acid solution. Eradication of the small spots followed careful treatment by this method. The following table shows by the increase in sulphates in the upper layers the extent of penetration of the acid solution by comparison of soil samples of each 6-inch layer before and after treatment.

TABLE 14.—ANALYSIS OF ROOT-ROT-INFECTED SOIL BEFORE AND AFTER TREATMENT WITH 1 PER-CENT SULPHURIC ACID SOLUTION. THE SOIL WAS THOROUGHLY SPADED TO INCREASE PENETRATION OF ACID.

Depth of sample (inches)	Parts per million						
	T.S.S.	Ca	Mg	Cl	SO_4	CO_3	HCO_3
Untreated—average three samples							
0- 6	738	45	15	30	trace	none	220
6-12	608	15	7.5	30	trace	none	195
12-18	511	15	15	20	trace	none	232
18-24	616	15	15	20	trace	none	256
24-30	630	15	15	20	trace	none	256
30-36	589	30	15	30	trace	none	268
Treated—average three samples							
0- 6	1,850	315	30	30	1,200	none	253
6-12	2,304	540	30	10	1,675	none	207
12-18	1,008	120	22	10	300	none	171
18-24	1,099	165	30	20	425	none	195
24-30	1,064	120	22	20	375	none	207
30-36	649	30	15	50	trace	none	256

The analyses in Table 14 show significant changes only in two columns—large increases in sulphates and calcium in the surface foot of soil and an appreciable increase from 12 to 30 inches, suggesting that the acid reacts with the surface layers and forms largely calcium sulphate. Effective use of sulphuric acid against root rot in the field would involve a method of securing greater penetration of the acid.

Taubenhaus, Ezekiel, and Fudge (146) have recently reported that of four soils changed to an estimated *p*H of 4.5 by sulphuric acid root rot disappeared in one, Tabor loam, an acid soil with a *p*H of 5.7. They consider the acidification of highly calcareous soils impracticable.

Gypsum

Calcium sulphate or gypsum can be used to add calcium to the soil, at the same time making it more acid rather than more alkaline. Taubenhaus, Ezekiel, and Fudge (146) report that the addition of 1 per cent by weight of gypsum to two different soils failed to reduce or control root rot.

Aqua ammonia

Neal et al. (78, 86, 87) working with aqueous solutions of ammonia found that a 0.1 per-cent solution would kill the root-rot fungus in twenty minutes under laboratory conditions. They then tried drenching the soil around root-rot-infected cotton plants with ammonia solutions and found that the plant would tolerate a 4 to 6 per-cent solution which was fatal to the fungus, while 8 per-cent solutions were very toxic to the plants.

Some preliminary experiments (118) on infected fruit trees in Arizona using solutions of aqua ammonia (29 per cent) at dilutions of 2 to 10 per cent proved too toxic for the peach, pear, and plum trees treated. Solutions above 4 per cent resulted in quick death of the foliage and blackening of the inner bark and cambium up to 3 or 4 feet above the soil line. A series on alfalfa with concentrations from ¼ to 5 per cent showed toxic effects above 1 per cent. Later applications of ½ to 1 per-cent solutions to peach trees followed by an irrigation showed no toxic effect.

After two years' experiments, the treatments were abandoned in favor of ammonium sulphate as the aqua ammonia was very unpleasant to handle in the field and seemed to have an undesirable effect on certain soils to which it had been applied.

Ammonium sulphate

The common commercial fertilizer, ammonium sulphate, was found to be, in common with other ammonium compounds, toxic to the root-rot fungus when applied at a sufficient concentration (118). Ammonium sulphate has proved the most valuable chemical for the treatment of infected trees and shrubs and for the protection of adjacent plantings threatened with infection, as it can be applied to living plants without danger of injury if directions are followed, and it is inexpensive and easy to obtain and

Plate XXVII.—Effect of ammonium sulphate treatment of pecan trees infected with root rot. *A*, Treated tree recovering; *B*, diseased tree showing scant foliage; *C*, check tree, diseased, not treated; *D*, severely affected tree cut back and treated.

apply (Plate XXVII). Ammonium sulphate is sold by almost all dealers in commercial fertilizers. The price varies locally from $3.25 to $4.50 per 100-pound sack, or $40 to $45 per ton. The treatment has been widely used in Arizona since the method was given to the public in 1934 (119).

Delay often fatal.—Trees or shrubs should be treated immediately after discovery that they are affected by root rot, as even a few days' delay may jeopardize their chances of survival. Trees or shrubs which are shedding leaves or whose leaves are drying rapidly should be immediately cut back to the extent of removing one half the crown, or even all the foliage, leaving sufficient scaffold branches to produce a well balanced top when growth is resumed. This drastic treatment is necessary for trees showing marked distress, as these trees will usually be found to have up to 90 per cent of their roots dead or infected by root rot, and they are unable to support the foliage, which promptly dries out.

The treatment aims to do two things: (1) drench the soil in the entire area occupied by the tree roots with a solution of ammonium sulphate strong enough to kill the root-rot fungus without injuring the tree roots, and (2) to leave in the soil a large amount of quickly available nitrogenous fertilizer, which will stimulate the tree to rapid growth and replacement of the roots killed by the fungus. The same inexpensive application accomplishes both results.

Method of application.—The first step is to loosen the soil around the diseased trees or shrubs by cultivation or spading to aid water penetration. Next a small border (dike) should be built around the area not smaller than that shaded by the branches of the tree. In case of upright-growing trees, the border must extend beyond the branches, as the aim is to include an area covering practically the entire root system of the infected tree.

Apply the dry ammonium sulphate to the surface of the soil within the basin at the rate of 1 pound for each 10 square feet, equivalent to 4,356 pounds per acre, or approximately ten times the amount ordinarily applied as a fertilizer. A basin 10 feet square or a 12-foot circle will require 10 pounds; a basin 14 feet square will require 20 pounds; a basin 20 feet square will require 40 pounds; a 20-foot circle, 30 pounds (20 x 20 x ¾). Scatter the sulphate evenly by hand after breaking any lumps, screening if necessary. Hoe the salt lightly into the surface soil to prevent uneven distribution by washing.

Apply water from a ditch or hose until at least 3 to 4 inches of water have been applied to the basin. Enough water should be used to wet the soil to a depth of at least 3 to 4 feet. The amount of water will vary with the nature and wetness of the soil treated. Insufficient water will expose the roots to a solution strong enough to kill them.

Alternate method.—Another method of application may be used where treated plants stand in lawns or other places where it is not desirable or convenient to impound water. Dissolve the ammonium sulphate, at the rate of 1 pound to 10 gallons of water, and apply with a sprinkling can at the rate of 1 gallon to each square foot. Immediately set sprinklers on the area and let them run until the soil is wet to a depth of 3 or 4 feet. This may be tested with a soil auger or, lacking that, an iron rod which can be forced into the soil to the depth of wetting.

Care after treatment.—Treated trees and shrubs should be considered "in the hospital" and given extra attention, especially in regard to water supply, as the injured root system cannot cope with even short periods of drought. If the treated trees show any signs of looseness when subject to wind they should be supported by strong guy wires in at least three directions, as the root system is badly injured and the tree may blow down before the root system has recovered. The pepper tree and Chinese elm are especially liable to be uprooted by strong winds accompanying summer rains, and trees are often lost when on the road to recovery if adequate support is omitted.

A second treatment may be necessary in some cases, but not more than two treatments should be given in one year, or more than three treatments on the same area, as multiple treatments may build up a toxic concentration of nitrates in the soil.

Eradication is aim.—Treatment is recommended to eradicate root rot in small areas in ornamental plantings, etc., even if it is not possible to save the affected trees and shrubs, as treatment aims to check the spread of root rot to the balance of the planting.

Most valuable as a preventive.—The best response, of course, is secured in the case of trees not badly affected, or in the case of trees and shrubs which are not very susceptible to root rot. The treatment is likewise most valuable as a preventive measure and should be used on adjacent trees and shrubs when root rot breaks out in orchard or ornamental plantings. Since the root-rot fungus travels from the ends of the roots of infected trees to the healthy roots of adjacent trees, we find that the apparently healthy trees standing next to visibly affected trees nearly always show some root-rot infection. If treated promptly they may never show any visible sign of root rot, lacking treatment they frequently die the following year.

The treatment and technique used is new and in need of further

Plate XXVIII.—Pecan orchard showing recovery of root-rot-infected tree (at left) treated with ammonium sulphate two years before photograph was taken. This tree is alive and healthy five years after treatment.

experimental work to perfect and improve it, but it is given out at this time in the hope of providing means of saving many of the thousands of valuable ornamentals which are lost each year from root rot. The treatment has proved very successful on the following species: pecan (Plate XXVIII), Arizona ash, fruitless mulberry, Japanese privet, California privet, cotoneaster, pyracantha species, Japanese pittosporum, oleander, and pepper tree. Favorable results have been secured on many other species, but the amount of data available is insufficient to warrant definite conclusions.

Results with deciduous fruits have been less consistent and complicated by conditions beyond our control. Some recent data suggest that the treatment may not prove effective in soils of strongly alkaline nature or high lime content, but it may be possible to overcome this difficulty (118, 121).

FERTILIZERS AND SOIL AMENDMENTS

Early experiments with the various commercial and organic fertilizers and soil amendments seemed to offer little promise of control of the root-rot disease by any program depending primarily upon their use. More recent work has shown a definite value for organic matter, ammonium fertilizers, and sulphur. It is noteworthy, however, that the amounts found effective are much greater than those generally applied in agricultural operations (121).

Manure

Reports of investigators working in Texas where susceptible crops are grown without irrigation have on the whole indicated little benefit from the application of manures to reduce root rot, although increases in yield were secured. Scofield (108) concludes from a seven-year rotation experiment at San Antonio "that the use of farmyard manure has not materially reduced the injury from root rot." Taubenhaus and Killough (148) summarizing five years' experiments state that "it is doubtful if the addition of humus or manure to the soil will greatly influence root-rot control, although it may increase the yield of cotton." A later bulletin in 1931 by Taubenhaus and Ezekiel (139) reaffirms this position but offers no additional data. Ratliffe (99) summarizing a thirteen-year test at San Antonio, Texas, concludes that manuring reduces infection, but he does not consider it of great value for crops grown under natural rainfall in Texas. It should be noted that the above refers mostly to broadcast applications of manure.

King (45, 46, 47), however, found that 12 tons of barnyard manure applied in trenches under the rows to 1-acre field plots of irrigated cotton each year for four years progressively reduced the amount of root rot until the number of dead plants was negligible, although the disease was not eradicated.

More recently King et al. (17, 52) have shown by studies of the soil flora of manured and unmanured plots that the root-rot fungus

is more abundant in the unmanured plots, while the manured plots contained a dense population of the normal soil organisms engaged in the decomposition of organic matter, developing a soil condition temporarily unfavorable for the growth and activity of the root-rot fungus. There was also some evidence of parasitism of the root-rot fungus by certain soil fungi. Butler (8) found that the common soil organism, *Trichoderma lignorum*, was definitely antagonistic to the root-rot fungus.

Manure placed in trenches directly beneath the rows of cotton has proved successful under irrigation (47). (See page 392 for details of the method.)

Other bulky organic fertilizers

Our experiments (118, 121) have shown that other bulky organic fertilizers such as spoiled hay, straw, green manures, and weeds are roughly comparable to manure on the basis of their dry weight. In the Sacaton experiments (55) 8 tons of spoiled alfalfa hay or 15 tons of fresh alfalfa were used as approximately equivalent to 10 tons of barnyard manure.

It is evident that these substances must be incorporated in the soil in advance of planting a susceptible crop or woody plant, and data indicate that very liberal amounts must be used to be effective. Under certain conditions, therefore, generous use of bulky organic matter creates in the soil a more or less temporary condition unfavorable to the root-rot fungus, but the action is preventive rather than curative, as it is impracticable to apply organic matter to soils in which the root-rot fungus is already attacking the plant roots.

It appears from a recently published critical study of the decomposition of organic matter in soils of arid and semiarid regions by Oberholzer (90) that the decomposition is more rapid and more complete than in soils of humid regions, and that the very profuse liberation of carbon dioxide from the decay of organic matter has no significant influence upon the *p*H of the highly buffered and stable calcareous soils typical of such regions. Using 1 per cent by weight of air-dried organic matter (manure, alfalfa, and hegari) an amount equivalent to 10 tons per acre of air-dried organic matter well mixed with the surface 6 inches of soil, Oberholzer found that the bulk of the carbon dioxide resulting from the action of microorganisms is rapidly returned to the atmosphere, and that the first few weeks of active decomposition result in large increases in soluble salts, especially calcium bicarbonate, with some increase in *p*H (alkalinity). The above data lead to the conclusion that the effectiveness of organic matter is due almost entirely to the competition and antagonism of the microorganisms competing with the root-rot fungus in manured soils.

Commercial fertilizers

Early investigations (139, 148) failed to show a definite value from applications of commercial fertilizers in the usual amounts

(up to 400 pounds per acre), but some recent favorable results have been secured.

Ammonium sulphate.—Ammonium sulphate used in various amounts up to 400 pounds per acre has shown no definite effect upon the spread of root rot (121). Very much heavier applications which depend upon the toxic action of the ammonium sulphate in solution are discussed in the section of soil treatments above (see pages 380-84).

Nitrate fertilizers.—Nitrate fertilizers such as sodium nitrate and calcium nitrate are not recommended for use on root-rot-infected soil, as the nitrate nitrogen (in contrast with ammonia nitrogen) is favorable to the growth of the root-rot fungus and therefore is to be avoided (78).

Phosphates.—Phosphates alone were found to reduce the number of plants killed by root rot in certain Texas soils (43), but phosphates were most effective in combination with ammonia nitrogen.

Potash.—Potash fertilizers apparently have no effect on root rot, probably because most southwestern soils are well supplied with this element.

Ammonium phosphate.—Ammonium phosphate applied in rather large amounts has given favorable results in certain Texas and Arizona soils. Jordan et al. (43) report that the ammonium phosphates have shown marked effectiveness in accelerating early plant growth and maturity in certain seasons as a means of evading losses to crops due to progressive killing of plants by root rot.

Ammonium phosphate (16-20-0) has been used as a substitute for ammonium sulphate applied at the same rate or 25 per cent heavier for the treatment of trees and shrubs (see pages 380-84), and our results have indicated an equal effectiveness or some advantage believed to be due to the response of woody plants to the phosphate.

Mixed fertilizers

Mixed fertilizers applied at the usual rates for fertilization appear to have little effect. Reynolds and Rea (102) reporting on eighty-five co-operative fertilizer tests on the blackland soils of Texas find a significant increase in yield from the application under the rows of 400 pounds per acre of 4-8-4, 4-8-0, or 6-12-0 fertilizer, but the increase was not profitable on account of the low price of cotton prevailing during the test (1930-32).

Taubenhaus and Ezekiel (139) report little effect on root rot from various fertilizers applied to sandy-loam soil in small containers, except that root rot appeared to be practically eliminated by application of 5 tons per acre of a 4-8-4 fertilizer. This would be equivalent in nitrogen content to 1¼ tons per acre of ammonium phosphate 16-20, but the phosphate content would be 60 per cent in excess. It is probable that the potassium represented by the last "4" in the formula is of little or no importance. Reduced to terms of nitrogen content of ammonium sulphate, this

amount is equal to 1 ton per acre, a little less than one half of the amount recommended in our method of treatment of infected soils. It appears, therefore, that there is essential agreement in regard to the value of ammonium compounds alone and in combination with phosphates.

Sulphur

Early experiments on the application of sulphur to the highly calcareous blacklands of Texas showed no definite benefit resulting from any of the amounts tested up to 5 tons per acre (148). Later experiments (37, 146) indicate that in soils which are not highly calcareous applications of sulphur may eventually control root rot. Neal likewise found that slightly alkaline soils on the eastern edge of the blacklands responded to moderate applications of sulphur which changed their reaction from slightly alkaline to neutral or slightly acid and reduced the amount of root rot in susceptible crops.

Taubenhaus, Ezekiel, and Fudge (146) conclude, in summarizing the most extensive experiments thus far conducted on the relation of soil acidity to root rot, that soils originally acid or made acid by the addition of sulphur, sulphuric acid, or calcium sulphate are unfavorable to root-rot infection or continued survival of the fungus from year to year. They furthermore believe that it is impracticable to acidify highly calcareous soils, and that the value of applications of sulphur to noncalcareous soils is a subject for further experiments.

In this connection McGeorge and Greene (62) of the Arizona experiment station have recently shown that sulphur may well be regarded as a suitable substitute for organic matter in semiarid, calcareous soils because of its beneficial effects on the pH, phosphate availability, and physical condition of these soils.

While many of our Arizona soils are too highly calcareous to make the use of sulphur feasible for the control of root rot, it does prove of value in case of small areas or amounts of soil, or in slightly alkaline soils. Sulphur is too slowly oxidized to permit its use in case of plants already infected, as complete oxidation is a matter of months.[9] Sulphur might well be mixed with the soil in tree holes where it is desired to plant susceptible trees in a region where root rot is prevalent. One drawback to intelligent use of sulphur is that a soil analysis is necessary to determine the proper amount of sulphur to apply in order to bring the reaction to the desired point.

Lime

Applications of lime in various amounts up to 5 tons per acre failed to show any benefit to Texas soils (148) as might be expected from the fact that they simply make alkaline soils more alkaline. Arizona agricultural soils contain from 2 to 10 per cent

[9] In one of our experiments some of the sulphur applied to soil seemed unchanged after one year's time.

calcium carbonate (limestone) and the layers of caliche (soil cemented by limestone) contain up to 20 per cent and more, and each acre-foot of soil weighs approximately 4,000,000 pounds, so that each per cent of calcium carbonate represents 20 tons per acre-foot. Obviously small additions of lime would have very little effect.

BARRIERS

Under some conditions artificial barriers to prevent the spread of root rot from infected to uninfected areas are the most practical method of certainly checking its progress (58). A variety of materials have been successfully used but certain conditions must be fulfilled: (1) the barrier must present a continuous surface impenetrable by the fungus; (2) the barrier must have been laid in advance of the spread of the root-rot fungus; (3) the barrier must be deep enough so the fungus cannot travel under it; and (4) the barrier must be fairly permanent.

Open trenches

If deep enough, open trenches form an effective barrier against the spread of root rot but are subject to so many objections that they can rarely be used. King (56) found that open trenches 20 inches deep temporarily checked the advance of the fungus but that it passed under the trench. McNamara and Hooton (65) found that a 12-inch trench checked the advance of the fungus for about two and one half months, but that a 24-inch trench was effective to the end of the season. They suggest that the zone of lateral advance of the fungus in the Greenville, Texas, soils is relatively shallow, largely in the first foot of soil.

Artificial barriers

Artificial barriers such as galvanized sheet metal not less than 3 feet wide set vertically in trenches in the soil, the sheets locked together end to end (57); thin dikes of concrete; and dikes of crude oil or road oil well mixed with soil (one part oil to ten parts dry soil) (57) and applied in trenches are examples of physical barriers. Successful chemical barriers are dikes 3 inches thick of a mixture of one part of sulphur with forty parts of soil or slabs of sulphur ½ inch thick, both used in Texas (139), and copper sulphate and sulphuric acid applied to soil in trenches in Arizona (117). Copper sulphate was applied at the rate of 1 pound to each linear foot of trench, and the sulphuric acid at the rate of 1 gallon per linear foot. The trenches were dug midway between two rows of stone fruit trees in an orchard where root rot had been advancing at the rate of about one row of trees per year. Since the apparently healthy trees standing next to the trees dying from root rot are known to be nearly always infected, a row of trees was sacrificed to insure that the barrier was placed in advance of the fungus infection (Fig. 8). The trenches were dug to a depth of 3 feet, and a portion of the chemical was applied to the

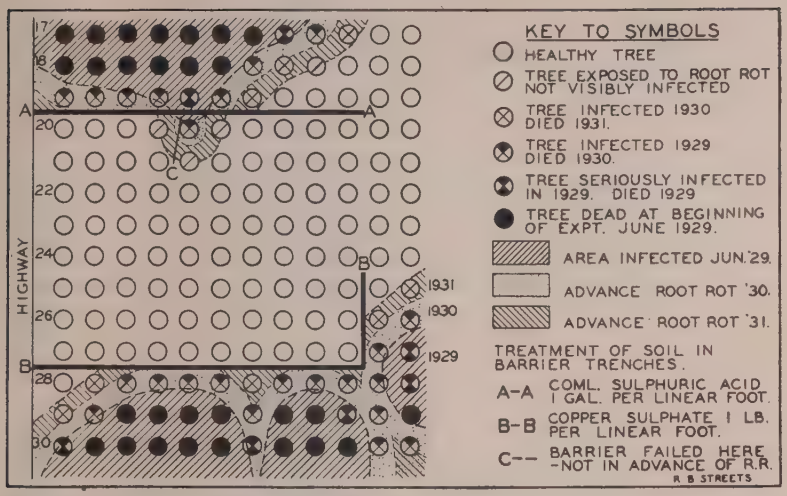

Figure 8.—Diagram of part of a peach orchard showing position of barriers in relation to advance of root rot.

bottom of the trench and a little water was run in to dissolve and dilute the chemicals. Each 6-inch layer of soil was treated as the soil was replaced and water added. The guard rows died of root rot the following summer but the barrier held for the three years that the experiment was continued (Plate XXIX). The only place the barrier failed was at a spot near one end of the guard row where a tree was infected by root rot when the trench was dug. The fungus had evidently already crossed the trenched area as the adjacent tree inside the barrier died late the next

Plate XXIX.—Peach orchard showing effective use of barrier to stop advance of root rot through the soil. When barrier was placed between the two rows one year previous all trees in the left hand row were alive. Root rot advancing from the infected area at left killed trees not protected by barrier.

summer (Fig. 8). At the end of three years the orchard was subdivided and a building boom obliterated all landmarks and most of the trees, so the experiment was abandoned.

Plant barriers

Four to twelve rows of grain sorghums kept free from weeds form a barrier which root rot will not cross. Three rows of sorghum held the fungus in check throughout a three-year experiment in Texas (139). It was found that cotton roots would not invade the area occupied by the sorghum roots. Corn or other immune cultivated crop should give similar results. This method is applicable to field crops, but it would be of doubtful value for tree crops where the lateral root spread would not be prevented by the barrier crop.

ROOT ROT IN VIRGIN SOIL

Virgin land, even the soils of desert mesas, cannot be guaranteed to be free from root rot, because the fungus is indigenous to this region. Recently spore mats of the root-rot fungus appeared in a trench dug on a desert mesa east of Tucson, in a district which had never been cultivated. In absence of indicator plants it is impossible to tell which soils are infected and which are not. On the other hand the heavier river bottom and valley soils are much more frequently infected than the lighter mesa soils.

SELECTION OF SOIL FREE FROM ROOT ROT

While the appearance of root rot in any form is definite proof of its presence in the soil, failure to find signs of root rot is, unfortunately, no guarantee that it is not present in the soil or may not appear at some future date. Since large sums of money could be saved by knowing in advance whether root rot would appear on any piece of land before attempting to plant it to susceptible annual or perennial crops or orchard, precautions should be taken to avoid infected land (95).

By examination of susceptible crops

The most reliable index of freedom from root rot is an examination of lands in susceptible crops such as cotton and alfalfa in September or October at the end of the growing season when the maximum effect of root rot is visible. Fields which show no evidence of root rot at this time may be considered as free from root rot as any lands in regions subject to this disease. Alfalfa fields two or three years old and free from root rot are better indicators than fields in annual crops such as cotton.

By air mapping

While small areas may be readily inspected and mapped for root rot on foot or horseback, on a large scale such a survey would be slow, difficult, and expensive. Aerial photographs of cotton

fields or other susceptible crops taken at the end of the growing season (October), as used by Taubenhaus, Ezekiel, and Neblette (133) and King, Hope, and Eaton (52), give a clear and accurate map of the infected areas showing definitely against the darker color of the healthy plants.

By presence of spore mats

During the period of summer rains, it is possible to see the fungus on the surface of the soil by looking for the spore mats (Plate VIII) following rains or in moist places following irrigation. The mats are most abundant in July and August, and their absence is not conclusive, as they are abundant in some years and scarce in others.

By presence of spore mats in dug holes

The root-rot fungus can be stimulated to the prompt production of spore mats on the walls or bottoms of holes or trenches dug in infested soil during the favorable season (July-August) if the soil is moist. Failure to produce spore mats is not conclusive but information can be gathered by observing tree holes, post holes, or holes dug from 2 to 4 feet deep especially to test for root rot.

By examination of soil for sclerotia

We may also examine the soil for sclerotia by washing a quantity of soil through screens and examining the residue for the small brown to black seedlike bodies. Again, although the presence of sclerotia is definite evidence of root rot, their absence is not conclusive, as our studies have shown them to be very erratic in their occurrence in Arizona soils. Certain experimental fields where root rot has been present every year for at least twelve years failed to yield a single sclerotium in some series of samples. Frequent requests to have determined the presence or absence of root rot in lands not planted to susceptible crops led the writer to make careful tests of the constancy of occurrence of sclerotia in known infected areas to see if a soil sampling method could be devised to determine root rot by the presence of sclerotia. Unfortunately, sclerotia were so scarce and erratic in occurrence that the method was not feasible (Table 13).

The only practical method of testing soil for the presence of root rot is to plant it to susceptible crops such as cotton or alfalfa for at least two years before planting to orchard, nursery, or other expensive crops.

QUARANTINE OF INFECTED AREAS

Following the discovery of root rot in certain areas in California, the California Plant Quarantine Service established a quarantine against the importation of soil or rooted plants from all areas known to be infected with root rot (35, 71). The Arizona Commission of Horticulture likewise maintains an inspection of com-

mercial nurseries and orders destroyed any plants found infected with or exposed to root rot, even if they are to be planted in root-rot areas. Private nurseries should use similar precautions, as root-rot infection is by no means uniform even where most prevalent, and care should be taken not to inoculate the soil further.

RECOMMENDATIONS FOR CONTROL IN SPECIAL CROPS

The following recommendations have been assembled for the guidance of persons dealing with Phymatotrichum root rot in soils under irrigation in Arizona and districts of similar soil and climate.

COTTON

Badly infected fields should be taken out of cotton and planted to nonsusceptible crops for three years. It is often possible to divide a field to separate the infected area from the non- or slightly infected part and to place the infected area in a rotation program. Fields showing only a few small spots should have the infected areas treated with ammonium sulphate or manure.

The method of application recommended by King (47) is to open furrows 10 to 14 inches deep in the infested areas, apply liberal quantities of corral or other organic manure (10 to 12 or more tons per acre) in the furrows, cover the furrows by plowing out the ridges with a middle buster, and irrigate generously. Manure should be applied from thirty to sixty days before planting time to permit partial decay of organic matter before seeding. If the manure is loose in texture it may be necessary to firm the soil over the furrows with a packer or press wheel. Cotton seedlings may show temporary yellowness from this treatment, and occasionally slight browning of the leaf margins which can be corrected by a light irrigation. This treatment is much more effective if repeated for several years, as the root-rot fungus does not thrive in the presence of great activity of other microorganisms in the soil. The method should be applicable to other annual row crops in irrigated sections.

In some communities Stoneville cotton can be substituted for the varieties generally raised, as its early maturity and heavy first picking will give fair returns on infected land (see page 374).

ALFALFA

Badly infected fields should be plowed up and planted to nonsusceptible crops for three years. Moderately or slightly infected fields may be treated with ammonium sulphate or manure, and the infected areas replanted in the fall. The expense of replanting is small and even where no treatment is given, several cuttings of hay are secured before the disease again takes its toll.

TRUCK CROPS

Winter-grown truck crops in this state escape the disease by being grown during the months when root rot is relatively inactive. This is true of winter-grown lettuce, carrots, cabbage, cauliflower, turnips, and beets, which are all susceptible crops.

Summer-grown truck crops such as sweet potatoes, okra, and tomatoes are very susceptible and should not be planted on infected ground. Small root-rot spots may be checked by treatment with ammonium sulphate. Onions, asparagus, and all cucurbits (cantaloupes, pumpkins, squashes, cucumbers, etc.) except watermelons are resistant and can be safely planted on infected soil.

ORCHARD CROPS

Tree crops on account of their long life expectancy and widespread root systems offer a most difficult problem of control. A root-rot-susceptible cover crop should not be used in any orchard where root rot has appeared, for it will enable the disease to spread more rapidly.

Deciduous fruit

Badly infected orchards of stone or pome fruits should be abandoned, the trees removed and the land planted to nonsusceptible crops for three or more years. An effort should be made to check root rot on its first appearance in the orchard by treating affected trees as soon as the disease is detected. It is of much greater importance that the fungus be eradicated than that the affected trees be saved. The Marianna plum root, used as a rootstock for stone fruits by some Texas nurseries, is quite resistant (page 373) and should be tried in Arizona.

Small fruits

Badly infected plantings should be removed and the land put into a four-year rotation. All varieties of grapes commonly grown in Arizona are susceptible, but Champanel, Mustang, and Black Spanish have proved resistant in Texas, and *Vitis champani* offers promise as a resistant rootstock (139, 147h). These grapes have not yet been tested for adaptation to Arizona conditions.

Strawberry is immune to root rot.

Pecans

Arizona now has some thousands of acres of pecans, nearly all of them planted in areas where root rot is prevalent; in fact many acres were deliberately planted on root-rot-infected land as the result of a statement in a bulletin some years ago that the pecan was immune to root rot. While the pecan seems partially resistant, the young trees and sometimes older trees become infected and die unless given special treatment. Pecan groves should be watched closely and the roots examined for root rot whenever growth seems checked and the foliage thin and pale in color. Diseased trees should be treated with ammonium sulphate as soon

as infection is discovered. The pecan responds very well indeed to the treatment (Plate XXVII), and the per cent of recovery is high. Early treatment will avoid the loss of one or two years' growth and crops of nuts.

Citrus

The sour orange, almost universally used as a rootstock in Arizona, is highly resistant to the root-rot fungus. When in rare cases the disease attacks sour orange roots on citrus trees, prompt treatment with ammonium sulphate is sufficient to check the infection.

ORNAMENTAL PLANTINGS

The great variety of trees and shrubs usually crowded together in the average ornamental planting offers one of the most difficult problems in control, for the fungus once established passes readily from one host plant to another through the soil and interlocking root systems.

So far as possible resistant species should be used in areas known to be infected with root rot. Eucalyptus, blue paloverde, fan palms, feather palms, and sour orange are among the most satisfactory resistant shade trees. Among the most resistant shrubs are oleander, desert willow, pomegranate, honeysuckle, crape myrtle, and arborvitae. (See tables 5, 6, 7 for complete list of ornamentals and their relative susceptibility.)

A tree or shrub killed by root rot should never be replaced with one of the same or other susceptible species unless the soil has been treated (Plate XXX). Formaldehyde or carbon bisulphide

Plate XXX.—The section of hedge of *Cotoneaster pannosa*, *b*, from the arborvitae, *a*, to the Japanese privet, *c*, was killed by root rot in 1933. The area was treated with ammonium sulphate and the dead plants replaced. Photographed May, 1937.

should be used if remote enough from other plantings (see directions pages 377-78), otherwise ammonium sulphate should be used.

Existing plantings should be fertilized with manure and ammonium sulphate or ammonium phosphate. The first symptoms of root rot which vary according to the plant affected should be watched for, and the roots of any tree or shrub showing yellowing or shedding of leaves, or pale, wilted, or drying foliage should be examined promptly. Ammonium sulphate should be applied immediately to the infected area and, what is more important, all adjacent, susceptible trees and shrubs should be treated as a protective measure. It is safer not to move plants from within 20 to 25 feet of established trees affected with root rot, as the fungus may have followed the extensive root system of the tree and be transferred in moving apparently healthy plants.

Because root rot can be readily transmitted in soil, even in the absence of diseased roots, every precaution should be taken in securing soil for tree holes and ornamental plantings to avoid root-rot-infected areas as a source of soil.

NURSERIES

Since root rot can wreak havoc with closely planted nursery stock (134, 150) (Plate XXXI) and nurserymen must have stock which will stand inspection by state authorities, root rot cannot be tolerated in propagating fields. Only fields known to be free from root rot should be planted to nursery stock (see selection of soil free from root rot, pages 390-91). Barriers and treatment with ammonium sulphate or formaldehyde should be used to limit losses and eradicate the disease.

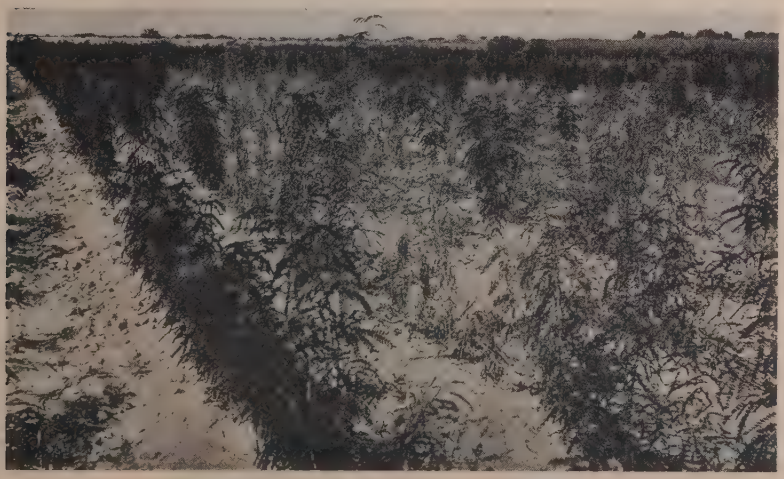

Plate XXXI.—Field of black locust seedlings showing heavy loss from root-rot infection (25 per cent of plants killed at time photograph was taken).

Steam sterilization or electric pasteurization of potting soil is advisable, as it eliminates not only root rot but all other soil-borne diseases, insects, nematodes, and weed seeds at a low cost (see page 378).

Susceptible weeds should be kept out of the propagating fields.

Nurseries maintained by the various branches of the federal government produce plants on a much larger scale than commercial nurseries for use in reforestation, soil conservation, and shelter-belt planting in the Southwest. The officials in charge of this work in Arizona are, however, aware of the possibility of spreading root rot with nursery stock and are following the recommendations of Mr. King of the Sacaton station and the writer in regard to testing of propagating fields for root rot by indicator plants, regular inspection of fields, and the restriction of infected areas to the production of grass seed (grass plants and other resistant plants for transplanting are grown only on root-rot-free soil).

Plate XXXII.—Seedling trees of Arizona ash growing in root-rot-infected soil. Seedlings of this resistant tree do not always escape infection (see Plate IX).

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SUMMARY

Phymatotrichum root rot is widely distributed in the semiarid Southwest. It is known to occur in southern Arizona, New Mexico, Texas, and the Republic of Mexico, and small areas in Oklahoma, Arkansas, Utah, and southern California. It has never been found in any other state or country.

Root rot is native to regions in the semiarid Southwest where the soils are alkaline and the winters are mild. It is occasionally found on the roots of certain native plants.

Root rot is one of the most destructive plant diseases known and causes greater losses than any other disease in regions where it is prevalent.

The root-rot fungus attacks an unusually large number of plants. At present over 1,700 species of plants are known to be host plants of root rot—a record approached only by the root-knot nematode with a list of over 1,000 host plants. Root rot attacks not only a majority of cultivated plants, including field crops, garden and truck crops, deciduous fruit trees, nut trees, shade trees, shrubs, and other ornamentals, but also weeds and native vegetation. The grasslike (monocotyledonous) plants, including grains, grasses, bamboos, palms, and bulb plants, are not attacked by root rot.

The greatest losses from root rot are encountered in cotton (loss in Texas in 1928, 440,000 bales worth $40,000,000), alfalfa, deciduous fruit and shade trees, and ornamentals. The total annual losses have been estimated at $100,000,000 in Texas, $50,000,000 more in the other six affected states, and $500,000 in Arizona.

Root rot is caused by the soil-inhabiting fungus *Phymatotrichum omnivorum* (Shear) Duggar. The vegetative (*Ozonium*) stage consists of cobwebby filaments and strands of interwoven filaments occurring on diseased roots. The spore-mat (*Phymatotrichum*) stage, consisting of cottony-white cushions which in a few days become a powdery mass of tan spores, is found on moist soil surfaces near dead or infected plants. A sclerotial (resting) stage, consisting of small tuberlike swellings which enable the fungus to survive unfavorable conditions, often occurs in the soil near diseased roots.

The root-rot fungus attacks the roots of susceptible plants causing them to decay. Affected plants wilt suddenly and often die quickly, sometimes overnight. Trees and other woody plants may die quickly or slowly according to the extent and severity of the attack. Plants may recover from one or more attacks of root rot and eventually die from repeated attacks.

The death of plants from root rot is due principally to mechanical injury of the root system with a result that the affected plant dies (usually in hot weather) from lack of water. There is also some evidence of poisoning of the plant by the fungus.

The root-rot fungus spreads from plant to plant along the roots or through the soil independent of roots for short distances.

The fungus filaments grow along the roots of susceptible plants and penetrate the roots in many places at once, killing the root cells as they progress.

The root-rot fungus overwinters in an active vegetative condition in plant roots infected but still living and remains more or less active on the roots of cotton, alfalfa, trees, or other perennials, or even winter annuals. Sclerotia or sclerotial strands may carry the fungus over winter or through other unfavorable conditions in a dormant state. The fungus may survive the winter on the roots of perennial or winter annual weeds.

Root rot is one of the most difficult of all plant diseases to control. The erratic behavior of the fungus when land is subject to rotation and clean culture and the great number of susceptible crops have made it difficult to outline practical and satisfactory control measures.

For field crops, rotation with nonsusceptible crops, together with clean culture to eliminate susceptible weeds throughout the period of rotation, is the most economical method of control. Rotations with barley, wheat, corn, or grain sorghums or other nonsusceptible crops for at least three years are necessary, since the sclerotia will survive that long.

Heavy applications of manure or other organic fertilizer have greatly reduced the amount of root rot in annual crops such as cotton. The treatment is preventive not curative and is not recommended for perennial plants already exposed to root rot.

A heavy application of ammonium sulphate (1 pound to 10 square feet or 4,350 pounds per acre) followed by a 3- to 4-inch irrigation drenches the soil with a solution of fertilizer strong enough to be toxic to the root-rot fungus without injurying the host plant. This treatment has proved very satisfactory on infected pecan, pepper, mulberry, casuarina, and bottle trees, and California privet, Japanese privet, pyracantha, cotoneaster, and pittosporum. It is likewise applicable to small spots of root rot in alfalfa and cotton fields. Two precautions are necessary for success with this treatment: first, to use the recommended amount of water, and second, to cut back the top of the affected tree or shrub to permit the root system to recover by reducing the demand on the injured root system for water. This is the only well proved treatment which can be used to save plants already infected with root rot.

Recent experiments have confirmed earlier findings that ammonium phosphate 16-20 used at the same rate and by the same method is equal if not superior to ammonium sulphate for root-rot control.

Soil disinfectants can be used to eradicate the fungus from small areas. To be successful the soil must be drenched with a solution of disinfectant or treated with gas to a depth of 4 feet (6 feet in the case of tree crops). The following solutions may be used: 1.25 per cent formaldehyde or ¼ per cent organic mercury.

Barriers may be used to limit the spread of root rot. Four rows of grain sorghums have checked the advance of root rot. Trenches 3 to 4 feet deep and 6 inches wide, filled with a mixture of soil and sulphur (2 to 4 per cent), waste or road oil (one part to ten parts dry soil), or crude carbolic acid will form a barrier. Mechanical barriers such as sheets of galvanized iron, walls of concrete, or slabs of sulphur have been used with success.

Applications of sulphur to root-rot-infested soils offer one of the most promising methods for the control of root rot but are still in the experimental stage, and no explicit directions can be given for dosage and method of application. It will no doubt prove practical in soils not highly calcareous, and of greater value as a preventive treatment than as a cure where plants are already infected.

Applications of lime, potash, sodium chloride (salt), and phenyl mercury acetate do not control root rot.

Cultural methods such as fall plowing, deep plowing, subsoiling, and fallow in most cases reduce the amount of root rot but rarely eradicate it. A single year of fallow has very little effect, but two years' continuous fallow has in a few cases eliminated the disease.

Root rot is not spread by the spore stage or by irrigation or flood water (except rarely by washing of sclerotia). The behavior of root-rot areas offers no evidence that the disease is often distributed by tillage implements or cultural practices.

In replacing trees or shrubs killed by root rot, resistant species should be planted or the soil should be treated carefully with ammonium sulphate or ammonium phosphate.

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